Information Driven Evacuation System (I.D.E.S.)

Samuel Edmund Grindrod

Doctor of Philosophy
The University of Edinburgh
2014

Abstract

The effectiveness of an emergency response during an incident is often affected by the lack of information provided to the people within the situation about the current conditions. Deaths in large-scale fires are often likely to have been caused by delays in the occupants receiving relevant information on the fire and egress routes [1]. This is why pre-movement behaviour, which is defined as the behaviour which occurs before an alarm is sounded and includes the activities which occur between the alarm sounding and the occupants beginning to move towards an exit, is believed to be generally more important to survival than the actual movement speed [2].

It is the unpredictability and complexity of human behaviour that is the most influential factor on the success / failure of an evacuation plan. Unfortunately, evacuation plans rely on the use of purposely designed egress routes which often are not the common everyday exits. These specifically designed egress routes, which an engineer may assume will be used during an evacuation, are often ignored by occupants due to the lack of information and noticeable distinguishing features. Having occupants moving in directions away from these intended routes may result in the increasing possibility of occupants finding themselves in a dangerous situation, ultimately leading to potential loss of life.

The value of a sensor-linked fire model has been demonstrated and the potential for interpretation of human behaviour shown [10]. However, there are many challenges in representing and interpreting data on human behaviour. Within most emergency evacuation situations, occupants will often walk past emergency exits without using them and exit through the main entrance or main exit, as displayed during an evacuation experiment held in IKEA in 1996 [11]. Problems occur because occupants will rely on the familiar exits over the closest

emergency exit, which could be potentially overcome by the use of an information driven evacuation system.

The main function of the Information Driven Evacuation System or I.D.E.S. is to provide occupants with information on the most appropriate egress paths within a building based on the development of the fire and the movement of other occupants. The system is a combination of real-time sensor data, a prediction modelling tool and the information driven way-finding tools. However, as all three processes are independent systems, a central server will be required in order to ensure that all the different processes are speaking the same language and that the information from one system can be understood by another. of the components within the system interact with each other.

The basis of the system will combine the use of sensors within a building and specific way-finding tools to give the I.D.E.S. the ability to change the information provided by the way-finding tools by having the sensors within the building interfacing with a computer server. This server will incorporate a modelling program that will have ability to assess the data gathered by the sensors, and use the servers "intelligence" (i.e. predicting capabilities) to alter the information provided by the way-finding tools. The server will also have the ability to use the sensor data to predict the development of the fire and the movement / behaviours of the occupants.

The way-finding tools used within the I.D.E.S. would have the primary goal of relaying the information to the occupants within the building through the use of both audio (e.g. directional speakers) and visual (e.g. flashing lights) capabilities. Basic audio and visual tools are already used as common features of an evacuation plan [9] and include exit signage and alarm bell/sirens. The computer model used as part of the "intelligence" of the server will need to have predicative capabilities that incorporate information provided in real time.

It is believed that the combination of these tools will be able to provide the occupants with the information required to evacuate the building in a safe and efficient way without causing confusion, thus reducing the possibility of stress and anxiety. However, the solution will only work if the combination of the tools, sensors and systems are able to be integrated into a central control panel that can be understood and used effectively by fire service and/or security staff.

The following is the Chapter breakdown of the thesis:

Chapter 1 discusses the nature of the problem that is to be addressed by the I.D.E.S. as well as the proposed solution and the overall concept of the system.

Chapter 2 provides an overview of the system to be developed as part of this thesis, via a graphical overview as well discussing the current status of the system and an higher level summary.

Chapters 3, 4 and 5 discusses the background research and information gathered on the current code requirements for an evacuation design, the current theories and completed research focusing on the human behaviour of occupants during an evacuation, and the development of computer modelling programs and their historical implementation.

Chapter 6 focuses and describes the development of predictive modelling, the limitations that dictates the modelling process, the requirements of the I.D.E.S. modelling programme and a review of the possible programmes for their ability to be used as part of the system.

Chapter 7 covers each of the three evacuation experimental series that were conducted as part of this thesis. The purpose of each of the relevant experiment is covered, the results gathered, the analysis of the research, and how the results influenced the development of the simulation methodology.

Chapter 8 focuses on the development of the modelling programme, based on the experimental data gathered, and presents a feasibility study that will demonstrate how the system would work during a simulated real life evacuation based on the information gathered from the experiments using the updated CRISP program and the hypothetical installation of the system within an existing building, located in Auckland, New Zealand. The possible further evolution of the system is discussed in Chapter 10.

Declaration

This thesis and the work described within have been conducted solely by Sam Grindrod under the supervision of Dr Stephen Welch and Prof. José L. Torero. Where others have contributed or other sources are quoted, references are given in full.

Sam Grindrod
2014

Acknowledgements

When I first signed on the dotted line four years ago, to undertake a PhD thesis at the University of Edinburgh, I never imagined actually reaching the final stage, where I would be actually writing my acknowledgements. I wish to thank everyone who has offered me support and assistance to enable me to complete this undertaking.

Firstly my thanks must go to my Supervisor, Dr Stephen Welch who encouraged me to preserve and finish this thesis. Your patience and sound advice over the past four years has been invaluable. Secondly, I must thank my wonderful mother, Sue, who has been available to listen to me, when I found the going tough and to encourage me to achieve my goals. The most important person I must thank is my father, Keith, whose initial suggestion that I travel to the United Kingdom to broaden my horizons, has as a direct consequence, resulted in me reaching the point of submission for my PhD. He has always been there on the end of the phone and was willingly available for me whenever I made any requests including any financial assistance. Without him I would not be in the position I am and I am therefore dedicating my thesis to him. A very special thanks you for your love and for always being there for me.

There are three groups of people I have had dealings with during my time at the University of Edinburgh and to whom I must give a special acknowledgement. To my colleagues at Fire Lab I thank you for putting up with my singing and my exuberant personality. To my colleagues at Lund University I thank you for allowing me to participate in your experimental work but apologies for sometimes adding to the stress and finally to the Royal Society of Edinburgh for awarding me a J.M. Lessells Travel Scholarship which enabled me to spend time at the University of Lund, Sweden where I meet the most amazing and wonderful people.

Thanks now to all the fantastic people I met during my overseas experience who accepted me and allowed me to be myself and go a little crazy when I needed to and made my experience so much fun.

I must thank the people who had the biggest influence, whilst I was living overseas, and who were responsible for making Edinburgh my "second home". John W, Will L, Kyle, Neill, Rosie, Lucy, Maltby and Tasha. Thank you so much for the greatest nights out and the amazing trips away. Thanks for accepting me into your group of friends and taking me under your wings, you will never know how much that has meant to me.

To my amazing friends in the Edinburgh Korftball Club, thank you for some of the craziest stories I will never forget. Nicki and Steve even though our time in the same place was limited, we did have some of the best times of my stay in Edinburgh. I can't forget Stu, my brother in arms, who was always there for me. Toby, you have been one hell of a friend and I know I can count on you at any time. Kirsty, thank you for the epic nights watching action films, and for all those diverse conversations we had together. Kris, even though we gave each other a hard time, it was all in good humour and it was an honour to share a flat with you and call you my friend.

To my boys in Sweden, Johannes and Erik, and their amazing partners in crime Christine and Livia, I wish to thank you all for looking after me and making my time in Lund one I will never forget.

Finally, I have to thank my colleagues and friends at Homes Fire Auckland, who have been there for me during the toughest times while completing this thesis. I thank you all for your patience and assistance over this past year.

To all the people I have not mentioned, I have not forgotten you. My thesis means more to me than a step forward in my career, as the memories and friends I have made over the past four years are priceless, and I would not change this experience for anything.

Come whatever may.

Contents

List of Figures:

List of Tables:

1 Nature of the Problem

1.1 Current Situation

The effectiveness of an emergency response during an incident is often affected by the lack of information provided to the people within the situation about the current conditions. Deaths in large-scale fires are often likely to have been caused by delays in the occupants receiving relevant information on the fire and egress routes [1]. This is why pre-movement behaviour, which is defined as the behaviour which occurs between the alarm sounding and the occupants beginning to move towards an exit/safe path, is believed to often be more important to survival than the actual movement speed [2].

The problems that can occur during an evacuation are often caused by providing the occupants with incorrect, vague or incomplete information [3]. This can lead to the occupants becoming overwhelmed and/or stressed (given the delay in their response), reducing their ability to come up with viable actions and then execute them. Therefore, it is very important to provide accurate and accessible information during the pre-movement phase to reduce encourage and facilitate the decision-making process and reduce stress levels in the process.

The success of an evacuation is dependent upon the ability of the occupants to evacuate without being exposed to hazardous conditions. Unfortunately, uninformed occupant behaviour can lead to unexpected responses making the process of an evacuation, and the overall success, more difficult to manage leading to an increase chance of the failure of an egress solution.

Evacuees will often use the more commonly used exits during an evacuation as these are more familiar. Unfortunately, evacuation plans rely on the use of purposely designed egress routes which often are not the common everyday exits. These specifically designed egress routes, which an engineer may assume will be used during an evacuation, are often ignored by occupants due to the lack of information and distinguishing features. Having occupants moving in directions away from these intended routes may increase the probability of occupants finding themselves in a dangerous situation, ultimately leading to potential loss of life.

Occupants may also delay initiating their movement towards safety and then the route that they employ to reach safety. This is often caused by occupants misunderstanding stimuli, both physical (flames, smoke, etc) and social (seeing others, receiving information from others, etc), and then mischaracterizing the nature of the risk posed by the situation.

The majority of issues discussed above that may occur during an evacuation, can often be attributed to a series of unforeseen events and/or lack of sufficient information on how an occupant is to safely evacuate from a dynamic scenario. Hence, it is these unforeseen events/evolving scenarios (combined with the complex evacuee response) that can lead to the failure of egress solutions and/or building designs and highlight how significant an assumption made during the design phase can affect the gravity of the failure. The failure of an egress solution/building design due to these factors is to be addressed through the use of the system that is to be developed as part of this thesis.

1.2 Related incidents identifying problem

The following are examples of two real life incidents where unforeseen events lead to the failure of the egress solution and how assumptions made in the design process failed to adequately address the situation that arose.

1.2.1 Woolworths Fire Manchester

The first fire incident occurred within the Woolworths store located near Piccadilly Gardens in the centre of Manchester on Tuesday the 8th of May 1979 [4]. At around 13:30 the first call to the fire service was made and fire crews were dispatched to the store. On arrival at the six story store the fire crews found smoke billowing from the windows where people were also calling out for help. It was thought at this time that there was around 500 customers and staff still inside the building. The fire crew, over the next two-and-a-half hours, fought to bring the fire under control while at the same time helping people out of the building via doors, windows and the roof. 10 people lost their lives in the fire with a further 47 people taken to hospital for treatment including six fire offices.

Even though the building was designed based on the relevant design codes of the time and met all of the regulatory requirements, a combination of design oversights and maintenance/procedural issues lead to a failure of the evacuation design within the building. The first issue was underestimating the effects of the material used within the furniture on the smoke development. As the fire was started by a damaged electrical cable within the furniture department, it ignited the budget furniture that was filled with polyurethane foam. This produced a large amount of thick toxic smoke. Not only did this smoke cause breathing problems, it also obscured the exit signs within the area of the fire – limiting the route information available. It was determined that the majority of the occupants who died as a result of the fire were found within the restaurant on the second floor, and due to the smoke being so thick, they could not find their way to the exits, which they had previously not used. In the absence of prior experience or procedural information, the occupants were not able to identify viable route options.

The second issue was caused by the occupants being committed to their prior activities; i.e. they were not sufficiently aroused by the cues to quickly disengage from their activities. [4]. When the alarms were sounded within the store the occupants who were in the restaurant, located on the same floor as the furniture department, ignored the alarm and continued to eat their lunch or queued for service [4]. Even when the visual signs of smoke from the fire became apparent within the restaurant they remained, continuing with their meals until staff intervened according to interviews conducted after the incident.

Thirdly, the effects of the fire load within the building were underestimated. At the time of the design it was not fully known how polyurethane foam would perform in a large scale fire. Hence, the designers were able to justify the omission of a sprinkler system within the building, which meant the fire was able to spread unhindered until the fire crews arrived. The aftermath of the fire led to stronger requirements for sprinklers to be used within large department stores and for the government to change the law to force furniture makers to use flame-resistant foam.

As the egress routes were hindered and made untenable by the presence of smoke, alternative exits were sought out by the occupants and by the fire service. Even though this cannot be considered as a design flaw, thick iron bars were installed on the windows on the upper levels of the building for security purposes, which is an example of the occasional conflict between safety and security an engineering must address. As occupants were trapped and ran to the windows to seek help, the fire crews made attempts to pry off the bars in order to use them as a means of escape. Unfortunately, they were unsuccessful and had to wait for specialist cutting machinery to arrive increasing the exposure of the occupants to the toxic smoke.

The Woolworths fire highlights how the lack of understanding of the fire load and material properties can lead to the failure of an evacuation design. In addition, the scenario indicated the importance of providing correct information to an occupant and how the lack of information during the development of a fire can lead to a significant delay in the response of the occupants, making the egress solution less efficient and, in conjunction with the structural issues highlighted, can limit the options available to the evacuating population. The behaviours briefly mentioned above will be discussed further within Chapter 3 of this thesis.

1.2.2 Mont Blanc Tunnel Fire

The second fire incident to be discussed occurred within the tunnel through the Alps that links Italy and France located underneath Mont Blanc on Wednesday the 24th of March 1999 [5]. At around 10:53 am a Belgian transport truck carrying flour and margarine stopped in the middle of the tunnel after the driver noticed cars coming in the opposite direction flashing their headlights, in an attempt to warn the driver about the white smoke coming out from under the cab. The driver attempted to fight the fire but was forced back by the developing flames. Two minutes later, tunnel employees triggered the fire alarm and stopped any further traffic from entering. At this time there was still at least 10 cars/vans and 18 trucks within the tunnel. Some of the cars were able to drive past the flame-engulfed truck while others managed to turn around and head back to the exit. However, as the dense smoke from the fire rapidly filled the tunnel, evacuation quickly became impossible. 39 people lost their lives during the incident.

As with the Woolworth Building, the Mont Blanc Tunnel was code compliant. However, what made this design more difficult was the fact it was being operated and regulated by two countries, meaning at the time each respective side only had to meet the requirements of their own countries codes. Hence, the single tunnel was design is two halves, with each half being designed to gain code compliance based on each of the respect countries design codes.

The tunnel was provided within two control rooms, one operated by the French and the other by the Italian authorities; as the fire was located on the "Italian Side" of the tunnel the Italian authorities had control of respective ventilation systems. The Italian operator activated the fan to push the smoke away from the Italian entrance forcing the smoke towards the French side of the tunnel. As the ventilation drove the toxic smoke back down the tunnel faster than anyone could run to safety, occupants chose to roll up their windows and wait for rescue. Most occupants, on activation of the alarm attempted to head towards the purposely designed fire cubicles. However, due to object affiliation [5], which is defined as an object with which a person feels they are closely associated or connected with, occupants were reluctant to leave their belongings and adhere to the emergency alarms. Once the occupant decided to finally leave their vehicles they were quickly overcome by the poisonous smoke.

The emergency procedure in place was for the occupants on hearing the alarm to leave their vehicles and follow the signage to the fire cubicles within the tunnel where they were to wait until rescued by the fire service. No secondary tunnel was provided as an egress route for the occupants. The original fire doors used on the cubicles were rated to survive the temperatures produced by the two hour ISO-curve (~1050°C), with some of the doors being upgraded to four hours during the 34 years of operation. However, as the truck was carrying a significant load of margarine, the fire load was greater than originally designed for and the fire heat release rate was far more intense than expected. The fire burned for fifty three hours and reached temperatures in excess of the design temperatures of the fire doors leading to the cubicles failing.

The previous discussion shows a critical error in the evacuation procedure for the tunnel; i.e. instead of installing a secondary tunnel that could be used for an egress route, the fire cubicle design was chosen that then failed. These cubicles in theory could have been a successful solution; however, due to the presences of a fire load greater than predicted the egress solution failed. Therefore, even if the occupants followed the evacuation procedure and used the cubicles they would have died within the fire.

The reason for the fifty three hours of burning was due to the (a) the intense fire conduction within the tunnel; (b) the additional air provided by the ventilation, which lead to the tunnel quickly filling with dense and poisonous smoke (containing carbon monoxide and cyanide) which in turned caused vehicle engines to stall because of the lack of oxygen (including fire engines), subsequently delaying access; (c) the fire melting the wiring and plunged the tunnel into darkness. Thus, as the fire crews attempted to access the fire via their vehicles they were prevented by abandoned and wrecked vehicles blocking their path, and they were forced to move in darkness through smoke that had developed to a level where no oxygen was available for engine use.

Due to these issues only vehicles on the French side were trapped as the extract system on the Italian side was activated in such a way that it pushed all the smoke in the direction of the French side, with only 12 of the initial 50 people trapped within the tunnel surviving due to the significant increase in the smoke concentration. 27 deaths occurred within vehicles and 10 died trying to escape on foot. Of the 15 fire fighters trapped in the tunnel, 13 were in serious condition when rescued and one died in the hospital.

The aftermath of the fire lead to the tunnel undergoing major changes. These included the installation of computerised detection equipment, extra security bays, a parallel escape shaft and a fire station in the middle of the tunnel complete with double cabbed fire trucks. The escape shafts were also given the ability to provide clean flowing air during an evacuation. Additional systems included video communication at each security bay that allow control staff to contact occupants within the tunnel in order to provide up-to-date information on a situation. Trucks are also now more thoroughly inspected before entering the tunnel.

The Monte Blanc Tunnel fire indicated the importance of providing occupants with up-to-date information on the development of a fire during of an emergency (for example informed evacuees near the fire could have been advised to evacuate past the fire towards the Italian of the tunnel instead of attempting to evacuate out of the French entrance) and the need for a tool that could potential have the ability to predict the development of a fire and alter the egress solution in real time. This is to be included as a possible feature of the system to be covered within this thesis.

1.3 Current Measures / Evacuation Design Methods

As mentioned before, both of the incidents previously described occurred within structures that met the required design codes of the time and were fully compliant. Both of the example above used different design approach to develop their egress solutions, with the Woolworths store using an approach known as prescriptive, while the Monte Blanc Tunnel used an approach known as a performance based design.

A prescriptive code design sets a series of design limits that a designer is required to meet as part of the egress solution; for example, a code may specify the number and capacity of egress routes required within a building, based on the design occupant load chosen by the engineer. A performance-based design is a goal-based approach which provides a designer with a greater freedom to apply engineering judgement to an egress design; under this methodology a solution may be considered acceptable providing sufficient evidence is shown that the concept will work, and safety targets will be achievable, typically through the use of models/simulations.

The basic framework of specific component of the prescriptive design codes now used within England are known as the Approved Document B on "Fire Safety". This framework provides many links to other standards, which historically were mainly British Standards (BS) but now include more European and international codes. The British Standards themselves are a large set of documents that include a number of standards relevant to life safety during egress and emergency evacuation. The underlying aim of the documents (and also within performance based code when pre-movement time are considered) is to provide the occupants with enough time to escape to a place of relative safety before the conditions reach the tenability limits. This requires the designer to use a set values from tables to design for the type of detection system to be used to detect of fire, the occupants pre-movement time which consists of the recognition time and the response time, the travel time (including queuing) to a place of relative safety and the movement within a place of relative safety (e.g. protected stairs or compartments). The objective is to limit the time taken to travel through areas within a building that could potentially be exposed to fire and smoke. There are two primary stages that occur before an occupant starts to evacuate, which are the time to alarm and the pre-movement time, which are assumed by the codes.

Each of the approaches uses assumptions to determine the requirement and type of fire safety systems used within a design - either provided within the prescriptive codes or are made by an engineer (based on previous case studies or research) as part of the performance assessment. However, as discussed the performance based design approach is heavily reliant on the engineer's ability to represent or account for evacuee performance. It is therefore important that the procedure in place can effectively inform and guide evacuee response.

1.4 Proposed Solution

In an attempt to address and take into account known behavioural limitations within the egress solution design process, to ensure the provision of timely and accurate information, a new method of providing occupants with up-to-date information based on the evolution of a fire needs to be developed.

The evacuee response is the result of a decision-making process and not based on random chance or actions resulting directly from a change in the environment. This process is sensitive to the information available, perceived and processed, which then is a key element in the action finally selected. As can be seen in Figure 1 below, developed by Kuligowski, each individual, before performing an action, can be seen as perceiving the available cues in a situation and interpreting how best to react based upon the risks, thus making a decision on what action to take before performing the action [7].

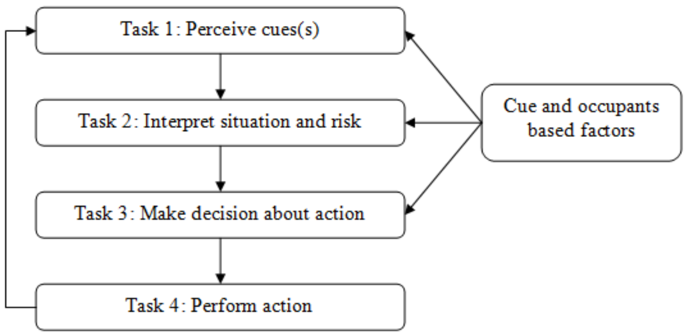


Figure 1: Decision-making Process [7]

During an evacuation an occupant can perceive/receive external physical stimuli (flames, smoke, etc.) and social stimuli (seeing others, verbal communication, etc.) that will influence the decision process. However, occupants may experience information overload, time pressure and uncertainty that can cloud their judgement [8]. The interpretation of the cues will lead the occupants to define both the situation and the risk to themselves and/or to others. It is during this process where they will ask questions that include, “was that a false alarm or is there really a fire?” The process of making a decision is based upon the occupants’ interpretation of the situation and the risks and will determine what the occupant will do next. Finally, the occupant will perform the action that they have decided on.

Therefore, according to Kuligowski’s model, the influence of providing occupants with up-to-date information during the decision making process is vital to the success of an evacuation. In order to combat the issues stated previously discussed, the proposed solution will need to incorporate a process that will be able to gather data about the fire in real time as well as providing information to the occupants that will help guide them to safety, with the goal of the system to help clearly define the evacuation scenario in order to help inform the evacuees during an emergency.

The system proposed within this thesis, as discussed in Chapter 2, will focus around influencing an occupant egress choice using information to drive the egress paths of the occupants with the goal of increasing the probability that the occupant will choose not to take the common/everyday route, when this is not the optimum choice, but instead take an unfamiliar egress route which has the potential to reduce the risk of exposure to danger. It is proposed that the influencing of the occupant’s egress choices will be through the use of a combination of both audio and visual way-finding tools. However, there is a possibility that during an emergency an available route that is deemed safe in the initial stages of an evacuation may become potentially hazardous and unsuitable for use. Hence, the solution will need to be able to adapt according to the evolving conditions.

1.5 Concept of information driven egress

The proposed solution will follow the idea of using information driven evacuation system or I.D.E.S. for short. The basis of the system will combine the use of sensors within a building (to get an accurate picture of the situation) and specific way-finding tools (to provide information to the evacuating population) to give the I.D.E.S. the ability to enhance the information provided to the evacuating population. It will do this through processing the information collected and projecting the implications of the current information on future conditions through the use of a modelling program based on a server. This will then update the information provided to the evacuating population by the way-finding tools to better account for the evolving conditions that might subsequently influence the procedural guidance provided. To do this, the server will need to use the sensor data to predict the development of the fire and the movement / behaviours of the occupants.

The way-finding tools used within the I.D.E.S. would have the primary goal of relaying the information to the occupants within the building through the use of both audio (e.g. directional speakers) and visual (e.g. flashing lights) capabilities. Basic audio and visual tools are already used as common features of an evacuation plan [9] and include exit signage and alarm bell/sirens. The proposed system will drive the information provided to the evacuating population. The computer model that provides the server "intelligence" will need to have predicative capabilities that incorporates information provided in real-time by the sensors.

It is believed that the combination of these tools will be able to provide the occupants with the information required to evacuate the building in a safe and efficient way, thus reducing the likelihood of exposure to deteriorating conditions.

The following chapter will provide a full system overview while discussing each individual component, the processes the system will make during an evacuation and how the information provided by the system will be given to the occupants, and the fire service, during the evacuation.

2 System overview

2.1 Graphical Overview

The value of a sensor-linked fire model has been demonstrated and the potential for interpretation of human behaviour shown [10]. However, there are many challenges in representing and interpreting data on human behaviour. Within most emergency evacuation situations, occupants will often walk past emergency exits without using them and exit through the main entrance or main exit, as displayed during an evacuation experiment held in IKEA in 1996 [11]. Problems occur because occupants will rely on the familiar exits over the closest emergency exit, which could be potentially overcome by the use of an information driven evacuation system.

The main function of the I.D.E.S. system is to provide occupants with information on the most appropriate egress paths within a building based on the development of the fire and the movement of other occupants. The system is a combination of real-time sensor data, a prediction modelling tool and the information driven way-finding tools. However, as all three processes are independent systems, a central server will be required in order to ensure that all the different processes are speaking the same language and that the information from one system can be understood by another. A high level overview of the Information Driven Evacuation System (I.D.E.S.) is provided in Figure 2 and provides a demonstration of how each of the components within the system interact with each other.

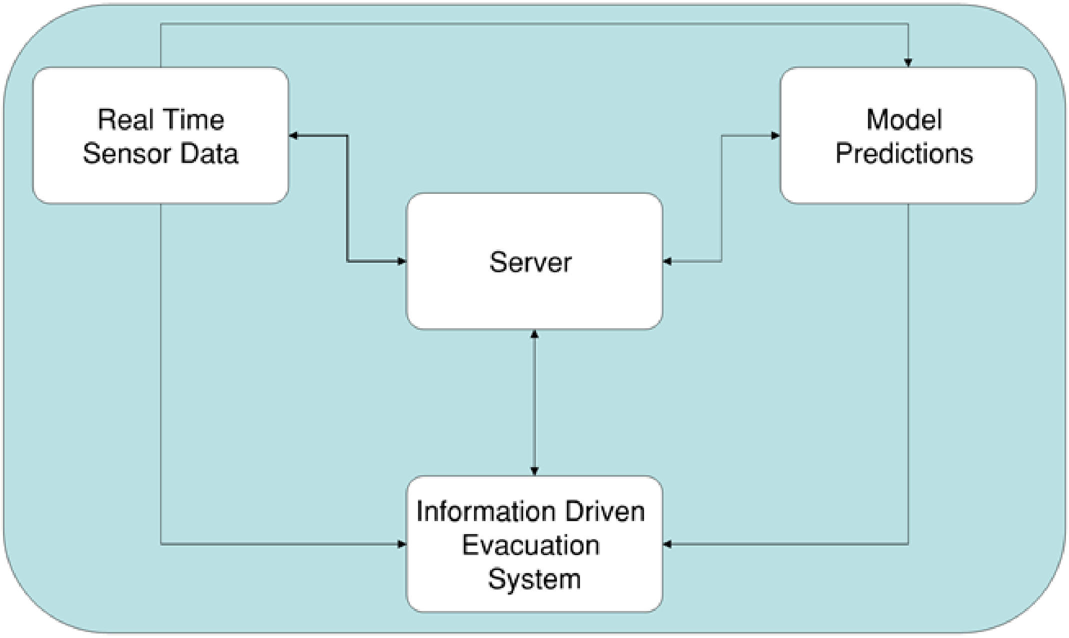


Figure 2: System Overview

Next in Figure 3 is a visual demonstration of the links between the sensor data and the background data and the process conduct by the system for checking for condition changes within the building, in order to determine if activation of the system is required. The continuous monitoring of the changes in state within the building involves the process of comparing the sensor data with the background base level data (i.e. normal conditions). Once a change of state is discovered the server is informed, which then activates the building alarm, the information driven way-finding tools and the model prediction software.

The modelling tool used as part of the I.D.E.S. will be required to have the ability to incorporate the information provided by the sensors in real-time in order to make prediction of the development of the fire and the movement of the smoke within the building. The model will also need in to have the ability to show how the behaviour of the occupants will be affected by the conditions and, in turn, how this will affect their possible choice of egress route.

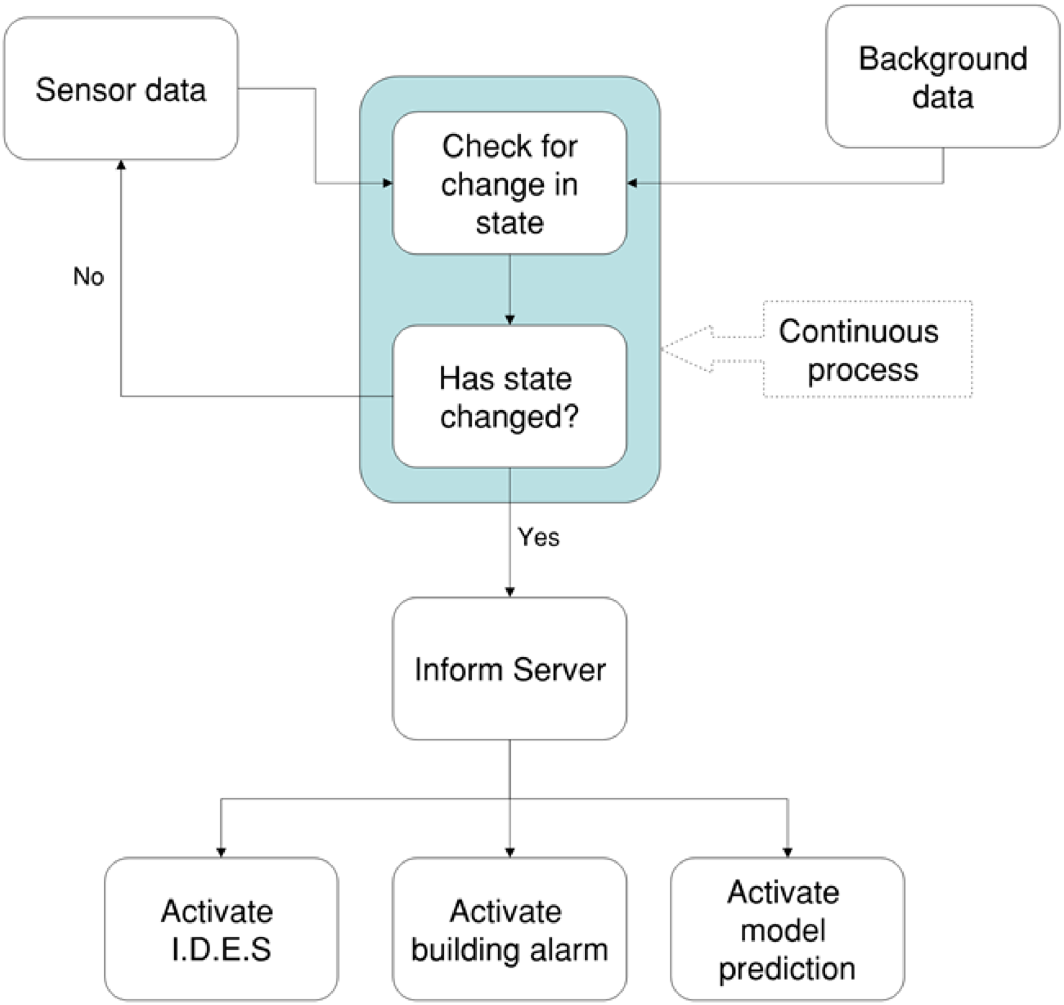


Figure 3: Real-time Sensor Information Breakdown

As the sensor data for each room is gathered it will feed continuously into the two prediction processes conducted by the modelling program. As can be seen below in Figure 4, each of the two prediction processes (fire development and egress movement) are a continuous incremental process that will run throughout the activation of the I.D.E.S. The information derived from each process will then be feed into the information driven evacuation system.

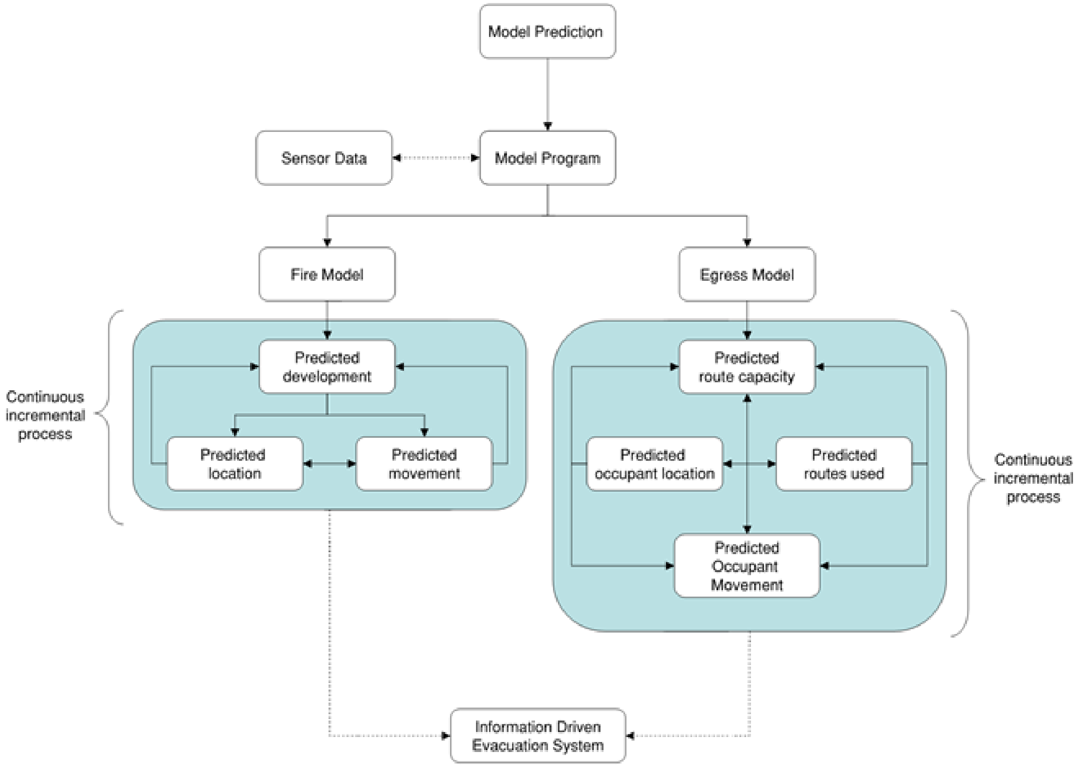


Figure 4: Model Prediction Process

The information driven evacuation system, as seen in Figure 5, is combination of three processes. The main process is the way-finding system that uses both audio and visual way-finding tools to help guide the occupants towards an exit. The goal of the proposed design of the way-finding system is to provide occupants with the location of the nearest safe egress route [32] to help guide them to safety while reducing their stress and anxiety levels. The main idea behind this goal is to keep the layout of the system simple so that the occupants can make a quick decision, without confusion, based on the information provided by the way-finding situation. Ideally, the tools will be able to provide real-time information to the occupants on the available egress routes with the purpose of reducing any confusion about alarms, therefore reducing the amount of time for occupants to start their egress movement.

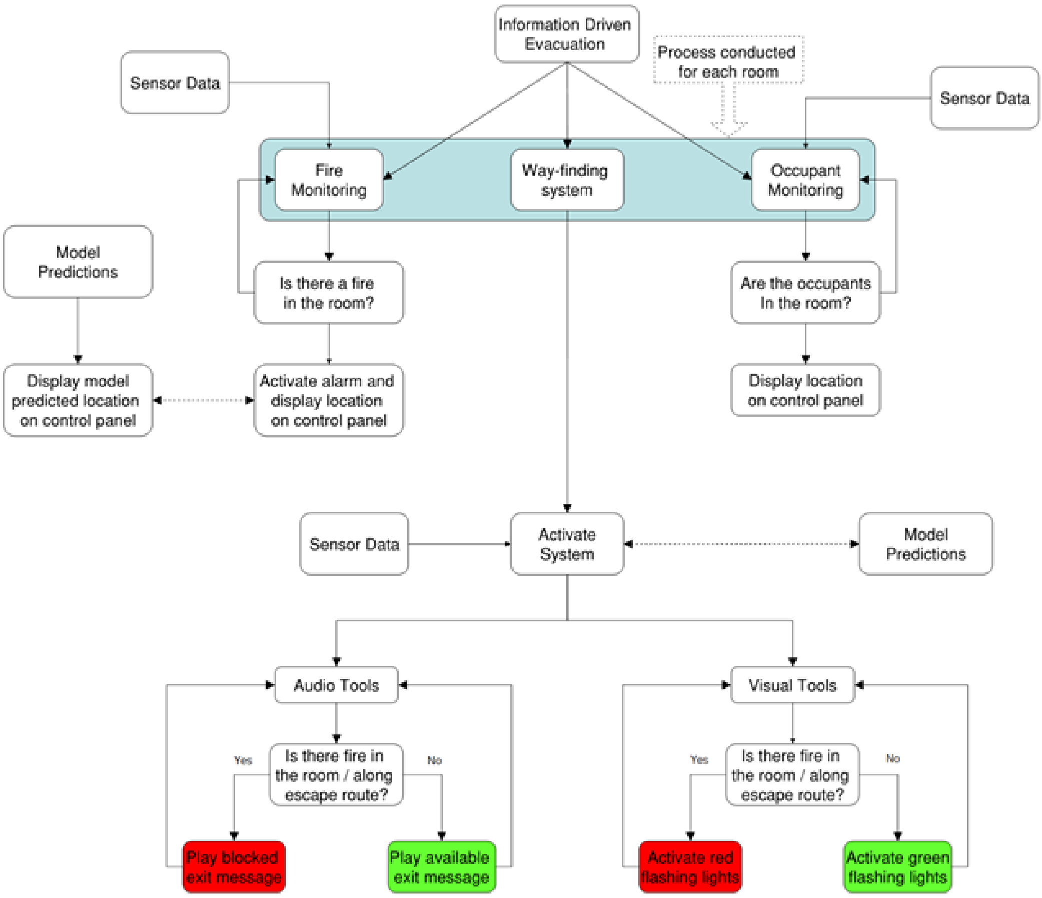


Figure 5: Information Driven Evacuation Process

In theory, if the system can reduce the reaction time of the occupants and direct them to a safe and close exit it would increase the effectiveness of the evacuation and the fire safety design of any building. Of course, the system should be usable by people of all ages and must be simple and easy to understand, since instructions on how to understand the information provided by the way-finding tool, in most cases, cannot be given to people prior to an emergency evacuation.

The system will also check for disruption in the connections between sensors, possibly due to the fire destroying the connections, which was experienced by Dr Sung-Han Koo during the final demonstrator test reported within his thesis [12]. If this was to occur before all of the occupants had evacuated the building the system would choose an optimal location for a temporary refuge and alert the operator in order to provide information to the rescue teams.

The other two processes conducted as part of the I.D.E.S. are the monitoring of fire and occupants within each room throughout the evacuation. The information provided by these two processes is also integrated into a central control panel that can be understood and used effectively by fire service and/or security staff.

2.2 Control centre/panel

Alarm panels are a requirement of the building code that incorporate a simple 2-D map of the building and the current sensors/alarm system. They can be used by security or the fire service to determine the likely location of the fire, based on which sensor zone has been activated, and the location of the main exits and, if installed, the hydrants/sprinkler inlet values.

The idea behind the incorporation of the fire and occupant locations upon a central control panel is to provide as much information as possible to the fire service in order to improve their abilities to fight the fire and save people lives. During the design of the panel it will be necessary to include the Fire Service as their input will be vital on determining the appropriate amount of information which should be provided and how it is displayed, in order to increase the usability of the panel. However, this will not be addressed as part of this thesis as it is considered to be part of the required future work. The task of finding an occupant within a smoke-filled room is difficult and time consuming, and it is not often known if any occupants are actually within the room being searched. Providing the fire service with information on the location of occupants compared to the location of the fire/smoke can limit the amount of time needed to safely search the building before the conditions become deadly.

It is proposed that the control panel for the system, located either within the control centre of the building or a location that can be easily accessed by the fire service, will build on the simplistic alarm panels required by the building code. The new panel will be able to display not only location of the individual sensors that have been activated within the system but the location of the fire/smoke as it spreads through the building and the movement of the occupants as they make their way to the exits.

To demonstrate how the control panel will work the following is an example of a fire as it develops over time within a simple single storey office building. When the alarm is activated, the initial location of the fire and the occupants within the building will be displayed upon the panel. At this stage of the fire all egress routes with the building are available and will be shown as green routes on the panel.

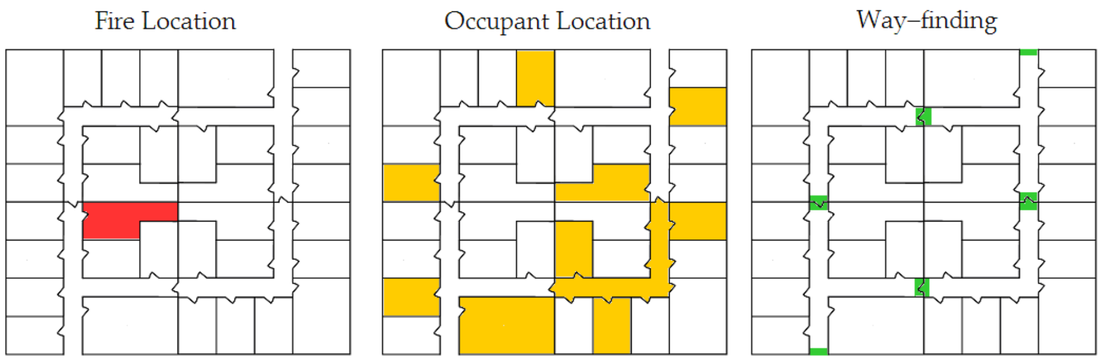


Figure 6: Panel display at start of fire

As the fire/smoke moves from its origin into other locations within the building these rooms will be highlighted. The occupants have started to move from their beginning location into the corridors and towards the available egress route and as it can be seen on the way-finding panel two of the exits have now started to display red LEDs meaning the route is compromised and the way-finding system is guiding the occupants towards the unaffected exit.

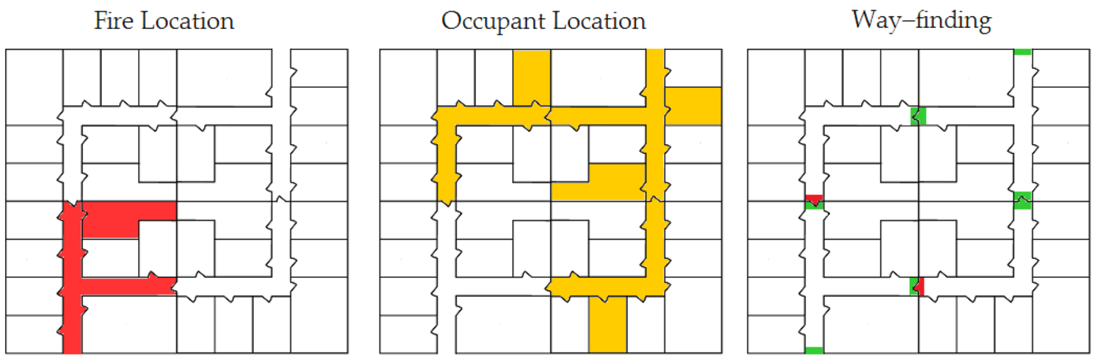


Figure 7: Panel display further into fire

As the fire/smoke continues it has now spread into another egress route, therefore, this route is now beginning to be displayed as "unavailable" upon the way-finding panel. The final occupants within the building are now located within the egress corridor nearest the exit route and are about to leave the building safely.

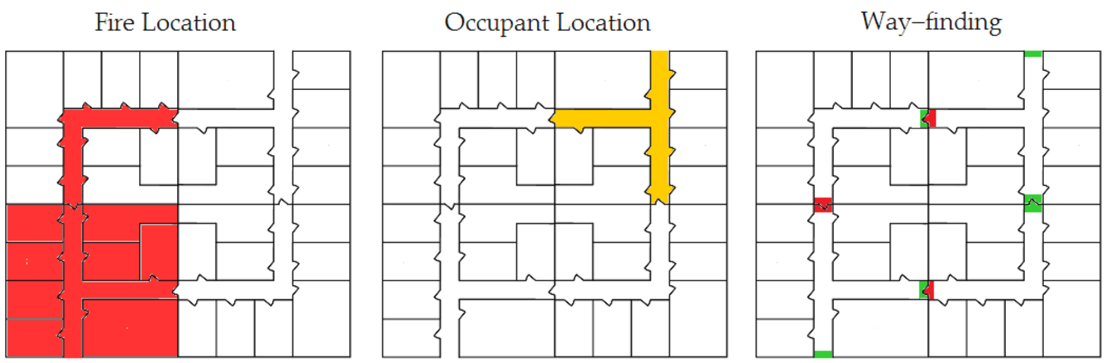


Figure 8: Panel display towards end of fire

The control panel requires the use of a computer software program that can access the information being provided by all sensors and produce the results upon the control panel in real time, while predicting the movement of the fire/smoke so that it can better determine which egress routes will provide a more efficient evacuation.

2.3 Current status of proposed system.

As it stands the majority of the processes and ideas used within the information driven evacuation system are in existence within published literature. However, the combination of the processes and how they will interact is current a research theory been carried out by some Universities, including Edinburgh, Greenwich and Lund Universities. Shown in Figure 9: Overview of System Status - Figure 12: Status of the Information Driven Evacuation Process, is a visual break down of which parts of the proposed system exist (indicated by the blue writing), which need further development (indicated by the green writing), and which are yet to be created (indicated by the red writing).

As can be seen from the overview in Figure 9 none of the processes exist in a capacity to which they can be used as part of the information driven evacuation system. They do exist and are in use as part of other system, however, they are not yet in a state where they can be combined to be used within the I.D.E.S.

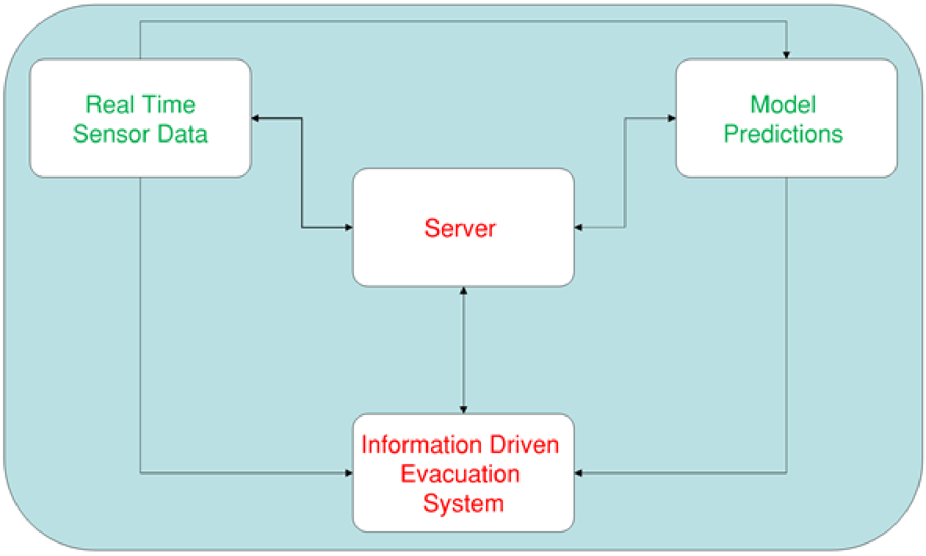


Figure 9: Overview of System Status

The real-time sensor data process (Figure 10) is mostly in an existent state due to the fact that the assessment of the change in state run compared to background data is the most common process that is frequently conducted by detectors throughout buildings. Each of the detectors have the ability to inform an alarm panel of the presence of a fire within the building which entails an activation of the alarm. The alarm panel can be considered a rudimentary form of the server required for the I.D.E.S., however, the ability of the server to activate the I.D.E.S. and prediction model has yet to be developed.

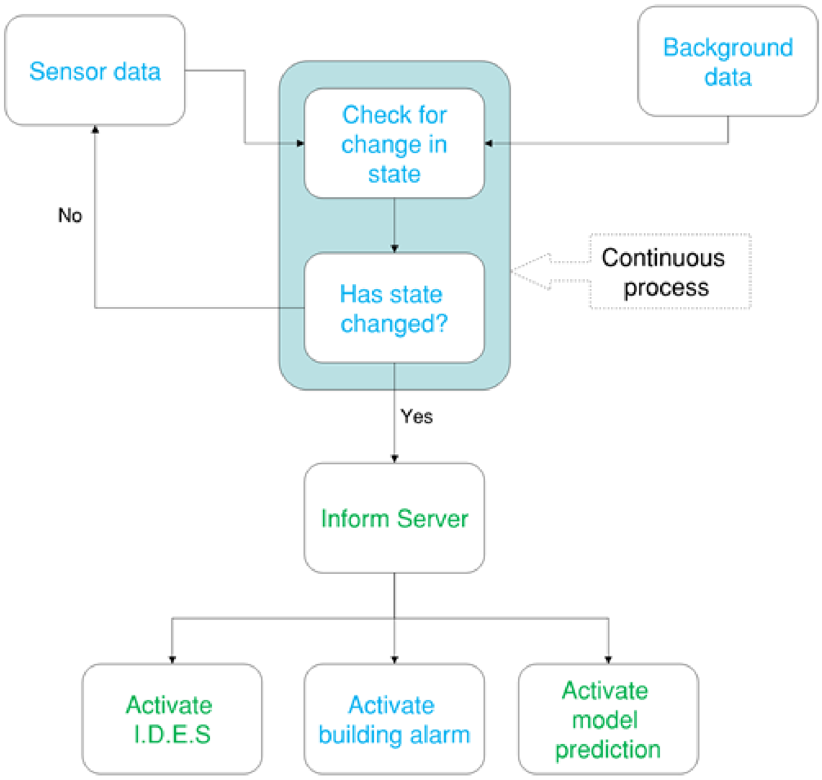


Figure 10: Status of the Real-time Sensor Information.

The two process conducted within the model prediction (Figure 11) process are also commonly used as part of an engineering design process. There are numerous amounts of modelling tools that can be used to predict the movement of the fire/smoke within a building. The use of incorporating real-time information from sensor to be used as part of prediction within a model has been recently demonstrated as part of the work completed by Dr Sung-Han Koo within his thesis titled "Forecasting fire development with sensor-linked simulation", which will be discussed later within Chapter 5.

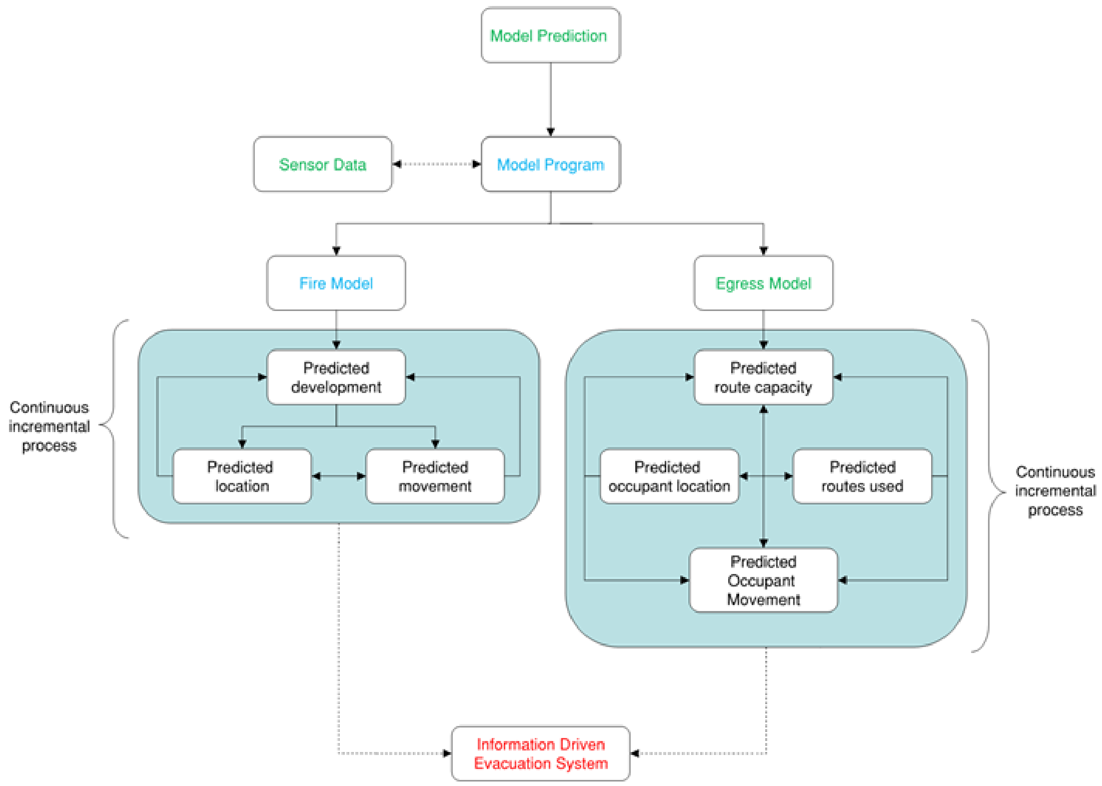


Figure 11: Status of the Model Prediction Process

There are many modelling tools that have been used to predict the movement of occupants through a building based on the location of a developing fire. However, only a small proportion of these tools incorporate a detailed human behavioural process that can be used to determine the interaction of occupants with the fire and other occupants in great details. The majority of models use fluid dynamics to model the behaviour of an occupant (i.e. movement is based on the number that can fit through a door), hence, interaction between the occupants and the environment is equivalent to the interaction between water flows and pipes. The ability for the current generation of egress models to incorporate real-time information from sensors in order to make prediction has yet to be included.

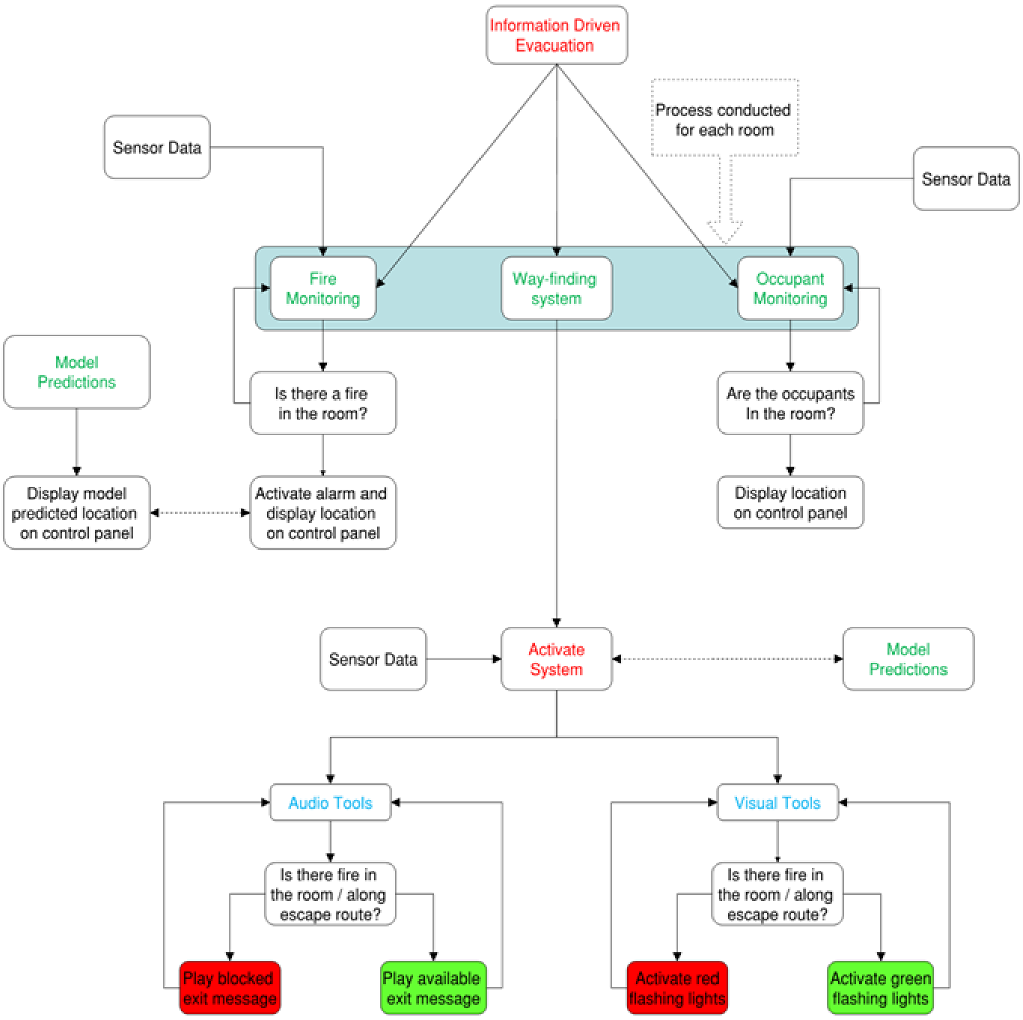


Figure 12: Status of the Information Driven Evacuation Process

The majority of tools and processes that form the I.D.E.S. (Figure 12) are readily available for use; however, how they interact and function together as a single entity has not yet been developed. Monitoring of fire and occupants can be activated using a variety of sensors and there are tools that have been developed that have the ability to display the location of each on a central server/panel. However, it is the ability for a server to incorporate modelling results and display these on the same panel that is currently in need of further development. This is a functionality of the central server that needs to be developed and not the panels themselves.

The way-finding tools that are to be as part of the system are currently in use as part of existing evacuation solutions around the world. However, it is the interaction of the server, modelling predictions and the ability to update and change the information provided in real time during an evacuation that is non-existent. Also, the interaction between the occupants and the audio and visual tools that will form the system has yet to be fully understood and is not able to be accurately displayed within the current generation of industry standard egress models. Hence, the modelling tool used for this system will also need to be able to assess the effect of the way-finding tools on the occupant's behaviours and egress choices.

2.4 Summary

In summary, the concept of the Information Driven Evacuation System was developed with the goal of improving the evacuation processes by making it more efficient. It is believed that the combination of real-time sensor data, a prediction modelling tool and adjustable way-finding tools will be able to provide the occupants with the information required to evacuate the building in a safe and efficient way without causing confusion, thus reducing the possibility of stress and anxiety.

The main function of the I.D.E.S. system is to provide an occupant with information on the most appropriate egress paths within a building based on the development of the fire and the movement of other occupants. The independent processes that have been determined to be needed within the system are given in the graphical overview earlier within this chapter. As can be seen with Figure 9- Figure 12 a large number of the process are currently in existence yet in order to be used as part of the I.D.E.S. further development will be required to ensure that the required interactions can be obtained. Hence, the aim of this thesis is to further develop the human behaviour and egress movement prediction tools to be used within the system that was currently indevelopment when the research was undertaken.

2.5 Chapter Structure

The following figures present the chapter structure of the thesis based on the four main components of the information driven evacuation system. As can be seen below, this thesis will be focusing on the development of the egress prediction modelling, the way-finding tools and how the they can be used to influence an occupant's behaviour and provide a high level discussion of the sensor data, the server development and the fire prediction modelling.

As seen from Figure 13, the model prediction system used within the system will be extensively covered throughout the thesis with the majority of the material focusing on the egressing model, the updates required and the prediction of the occupant's behaviour.

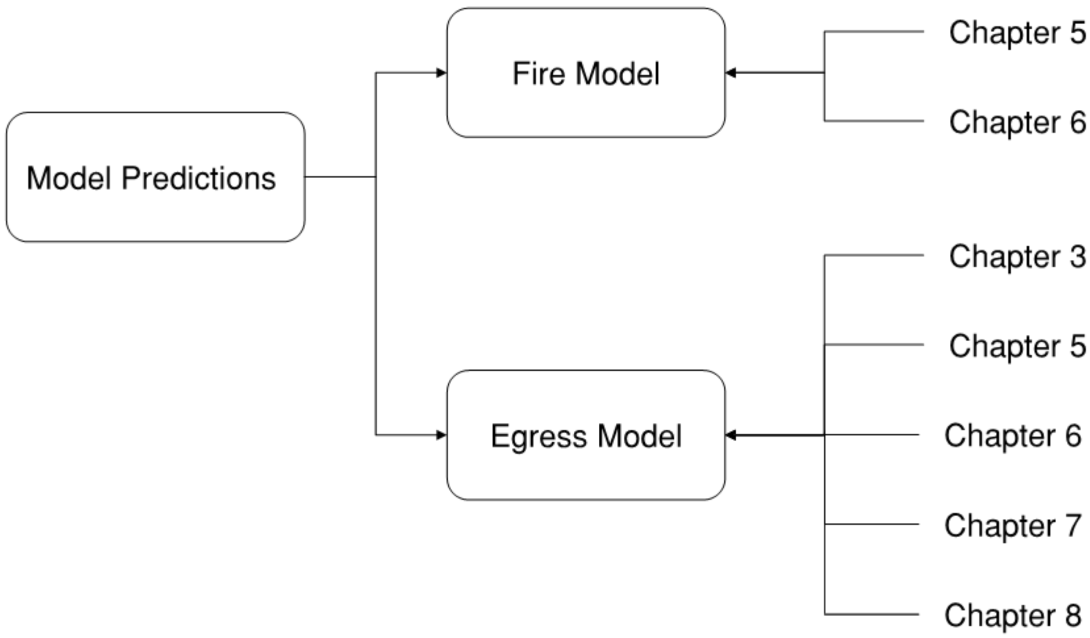


Figure 13: Chapters Covering Model Predictions

As with the model prediction egress system, the way-finding systems and how they influence the occupant's behaviour during an evacuation will also be extensively covered throughout the thesis. However, as seen below in Figure 14 and Figure 15 occupant and fire monitoring, sensor data and the server will only be briefly covered within Chapter 5 and 10.

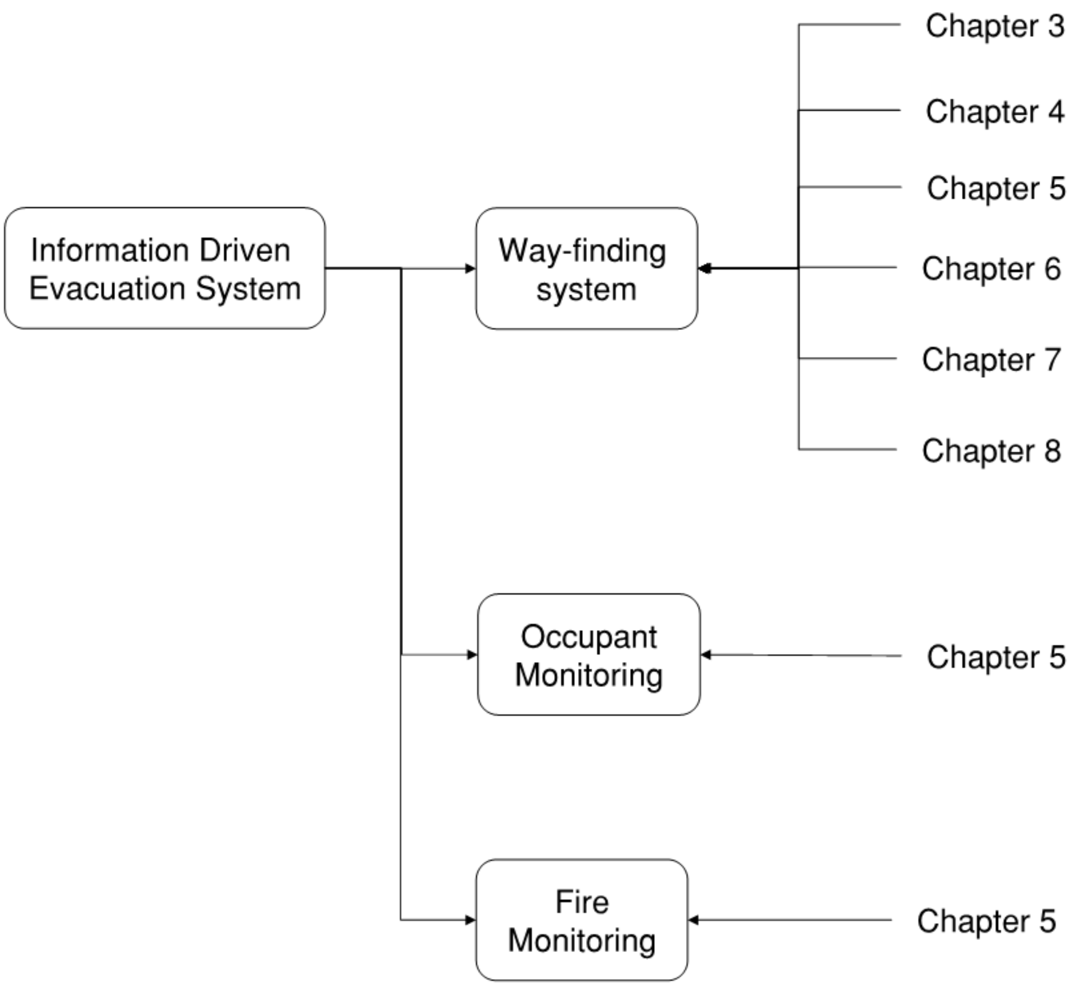


Figure 14: Chapters Covering the Information Driven Evacuation System.

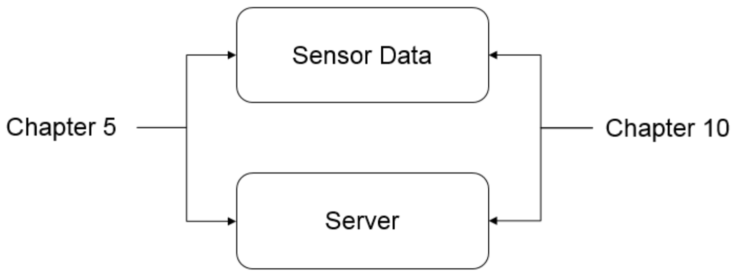


Figure 15: Chapters Covering Sensor Data & the Server.

3 Human Behaviour

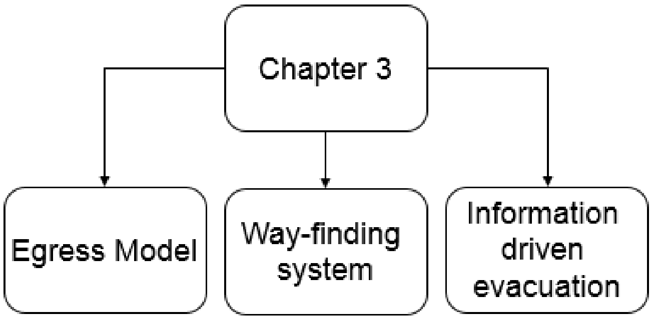


Figure 16: Topics covered within Chapter 3 compared to the system.

How an occupant behaves during a situation defines the characteristic of that individual, which is based on previous interaction and lesion learnt during their life time. No two individuals will ever behave in the same way nor will there ever be two identical situations. As a person develops it is the influences and education that they have had in life that shapes their decision making abilities/processes. This chapter will discuss how the decision making process is moulded by a person's past experiences, education and training and how these influence a person's behaviour.

As seen within Figure 16 above this chapter will cover the human behaviours which the egress prediction model will need to be able to predict, how the way-finding systems will influence the occupants and how the behaviour will influence the design of the system as well as how the system will influence the behaviours. The first factor to consider will be to determine the plausibility of using an information driven evacuation system to influence an occupant's behaviour during the initial stages of an emergency before they have made their own choice on when and how they will evacuate from the scenario.

3.1 Decision – making process

As discussed previously the action that an occupant performs during a situation is the direct result of the behavioural or decision-making process, and not based upon a random chance or actions resulting directly from a change in the environment. The understanding of how an occupant perceives/receives stimuli, either physical (flames, smoke, etc.) or social (seeing others, receiving information from other, etc.), is important as it will determine how an occupant behaves during an evacuation and how they came to the decision they make.

The manner in which an occupant perceives cues during an evacuation/emergency can be summarised into six processes [13] which include:

Process	Description
Recognition	How the occupant reacts to ambiguous fire cues will determine how they respond to a fire. It is dependent on the individual's experience, training and perception of risk.
Validation	The process of assessing the threat of the cues and can involve seeking information from other people to help validate the significance of the threat. Social factors may affect/inhibit validation responses.
Definition	This involves considering threat cues against other matters such as time and magnitude of the fire to interpret the threat.
Evaluation	Once the threats have been evaluated the occupant will decide upon an appropriate response, (time required to exit, means of exit, etc).
Commitment	Direct response to the fire by committing to an action, such as escape, raise alarm, etc.
Reassessment	Only applies if the attempted response by the occupant is ineffective or the action does not achieve the desired result.

Table 1: Cues during an evacuation/emergency [13]

As more research is conducted into the behaviour of humans during an evacuation the more complex the diagrams of behaviour are becoming. The human brain is not easily simplified and hence this is why more often than not occupants do not behave in predictable ways. A group of researchers at the U.S.

Department of Health and Human Services studied [14] the human behaviour that occurred during mine fires and used the information to develop a model to look at the judgement and decision-making processes. The model describes the decision-making process in a series of five elements; dictation of a problem, definition or diagnosis, consideration of available options, choice of what is perceived as the best option given recognised needs, and execution of the choice based on what has transpired. This model also takes into the account the factors that can have a large impact on the occupants' ability to solve complex problems in a limited time. The factors include an internal state that is the sum of the person's psychomotor skills, knowledge attitudes, etc., the uncertainty that could occur due to poor or incomplete information, stress caused by the current situation or a problem that may exist, and finally the complexity of the situation. The influence of stress can significantly affect an occupant's ability to make a decision that is beneficial for themselves and others around them.

Proulx attempted to create a decision model that incorporated the effect of different levels of stress on the choices made during the selection of an option [15]. The effects of stress will be discussed in depth in section 2.3 of this chapter. The following will discuss the stress model created by Proulx (Figure 17).

The stress model in Figure 17 [15] is the attempted illustration of a very complex problem in a simplified fashion. The construction of the model itself was based upon literature available at the time on information processing, decision-making, problem-solving and stress. It is accepted to assume that every person involved in an evacuation will feel some level of stress regardless of their age, sex, cultural background or experiences. As stated by Proulx, stress is not a destructive force and is a necessary state that will motivate occupants to react and act. In other words the evacuee will need to be motivated in order for them to evacuate and it is believe that feeling of stress will provide this motivation, however, it also has the potential to work in a negative way as discussed below.

Each of the five loops within the model describes how the occupants receive the information and how the level of stress and the interpretation processing system (PS) affects the feelings of the occupants. Stress will tend to change the occupant's feelings from one of control to uncertainty, fear, worry and possible confusion. This is due to the occupants having to keep processing information which sometimes can be irrelevant to the situation inducing self-concern.

Eventually, processing of the information will add an emotional load to an already stressful situation and increase the level of stress significantly. This can be overcome by the occupant adopting compensatory strategies that consist of investing more effort and concentration on the task (evacuation) and trying to control worrying thoughts. However, the effects of using compensatory strategies to lower the pressure in the processing system will result in causing fatigue and subsequently will lead to the manifestation of confusion, even if it reduces the stress and improves the efficiency of the occupants to make decisions.

Proulx model shows that fear will come before worry as the stress levels develop during an emergency scenario. This is because she believed that the pressure due to the occupant being overload with information will induce fear before worry as she defines fear as "the emotion felt due to the 'anticipation of pain'". Resulting in the idea that the occupant will first fear the unknown danger of a situation before they start to worry, developing thoughts such as "I'll never make it" or "I don't know what to do". In reality, the emotion felt due to the anticipation of pain could be determined to be either fear or worry, yet, for the purposes of her stress model she has defined the process as being fear before worry. In theory they could be interchangeable as the emotional she is describing change based on a researchers specific definitions of each during an emergency.

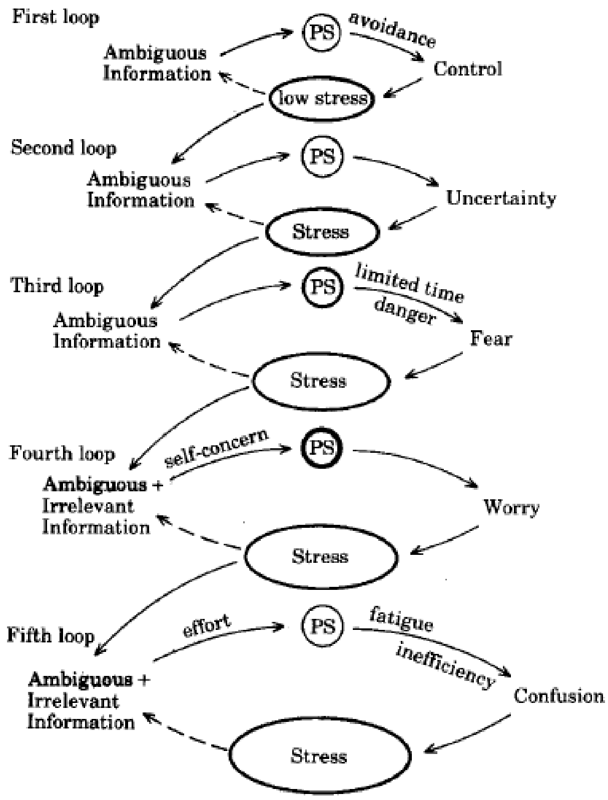


Figure 17: Proulx Stress Model [15]

As more research is conducted into the decision process of occupants the more complex the model tends to be. However, this chapter will focus on the education and training occupants receive about an evacuation and the behaviour that could occur in the pre-movement and movement phases of an evacuation rather, than on how complex the behavioural models can become.

3.2 Pre-evacuation & Evacuation movement

The behaviour of occupants during an emergency includes both their pre-movement activities and what they do during the movement phase of evacuation. Pre-movement behaviour is that occur before an alarm is sounded and includes the activities which occur between the alarm sounding and the occupants beginning to move towards an exit. As discussed in Chapter 2 the pre-movement time of the occupants often predicted incorrectly and often over-estimated, depending on the regulatory codes used, to ensure a building is designed with an available safety evacuation time (ASET) greater than the required safe evacuation time (RSET). The over-estimation is due to the fact that is it difficult to predict how the occupants will behave during the initial stages of an emergency. Research into the estimation of pre-movement and the behaviours that occur is difficult as it normally based upon evacuation experiments that do not necessarily accurately portray the feelings and situations occupants will find themselves in during a real fire evacuation. Interviews with occupants who have been within an actual evacuation have been conducted and recorded [18], [19], [20], however, it is uncertain if the evidence can be used to reliably describe pre-movement behaviour as it requires the occupants to remember everything they did and thought after a stressful situation, which can be difficult. The interviews are also often conducted a significant time after the events which can cause the occupants to forget or fabricate behaviours that they demonstrated.

Proulx [16] suggested that there are three primary phases for the evacuation process, perception – interpretation – action, which affect the pre-movement behaviour of occupants. There are factors that can affect the occupant's behaviours during the initial stages of an evacuation, which include the alarm type, the alarm intensity, the presence of person with authority, the frequency of false alarms, occupant activity, occupant characteristics, etc. The behaviours that have a huge significance during the pre-movement period include the occupant's reaction to the alarms, the (subconscious) decision to become a leader or to be led and the occupant's activity before the alarm is sounded.

The purpose of an alarm system is to warn the occupants of a situation and to facilitate the evacuation of the building towards a safe area. The success of the evacuation is determined by how the occupants react to the alarm, as well as other factors including availability of egress routes (discussed previously). When an alarm is sounded occupants will often wait and see if the alarm continues to sound just in case it is a "test" and therefore they are not required to react. This may be due to the occupants experiencing frequent false alarms within a building, which will reduce the effectiveness of the alarm and may cause occupants to ignore the alarm altogether. If the alarm continues for a significant time occupants will begin to take notice and start looking for signs of an actual fire or try to ascertain if it is just a fire drill. The decision to evacuate is often based upon the occupant perception of physical (smoke, heat, etc) or social (influence of others, etc) cues. Certain types of alarm are more effective than others and the more informative and intrusive the alarms are the more effective they will tend to be, which will be discussed within Chapter 4. However, if an alarm is too loud, it may hinder communication between individuals which can significantly affect the evacuation process [14]. The influence of others within an evacuation situation can help occupants focus their goals and gather necessary information. The sharing of information is very important and can help prepare the occupants mentally to evacuate a situation that they are finding stressful and boost their confidence through the evacuation.

Whilst the interaction with other occupants is very important, the role an occupant takes during the interaction is more significant in assuring an effective and efficient evacuation. "To become a leader or be led" is an important choice that must be made by each occupant before deciding to evacuate during an emergency. A leader is often seen by other occupants as a person with a designated responsibility (a fire fighter or member of building management staff) and occupants appear to be more willing to leave if a leader of some sort is present and urging them to escape. However, in some situations a person of authority may not be available and the choice above will still be need to be made.

It is often the fear of being embarrassed in front on one's peers that keeps people from taking charge and control of a situation. A psychological study based upon the research conducted by Latane and Darley showed this phenomenon using a group of people waiting in a room [17]. The people were to fill out a form for a job interview and the alarm would sound while eventually pumping in fake smoke into the room to see their reactions. The catch of the experiment was the fact that all but one of the people were paid actors who were told not to react to the alarm or the smoke in order to see if the other person (the non-actor) would react to the smoke and if they would begin to evacuate by themselves or try to get the others to evacuate. The test participants would display anxiety while looking around the room to see the reaction of the other participants. The majority of participants choose not to speak up and waited till they were told by a member of authority, normally 15 – 20 minutes into the experiments that they had to evacuate due to the smoke/alarm.

If an occupant is engaged in an activity, for example queuing for tickets, or sleeping, prior to the sounding of an alarm they may be more reluctant to leave the building. There have been cases where occupants have shown reluctance to move even once they have seen the smoke from the fire. The previously outlined case study of a fire that occurred within a Woolworth store in Manchester in the furniture department showed this behaviour [4]. When the fire occurred and the alarms began to sound the occupants within the café, located on the same floor as the furniture department, ignored the alarm and continued to eat their lunch and queue for service. Even when the signs of smoke from the fire became visual within the café they refused to leave their meals and it wasn't until they were told to by a member of staff that they began to evacuate.

Once a decision is made either by an individual or a group of occupants to begin evacuating towards safety the behaviours will change from that displayed in the pre-movement phase to those that will eventually dominate the movement phase.

The time for the occupants to travel to safety can be calculated based on a series of formulas that have been validated using movement experiments. However, these formulas do make assumptions on how the occupants will behave in an ideal evacuation. One assumption is that all occupants will know all the exits and will use the exit that is closest to them, thus reducing the chance of queuing.

However, evidence shows that occupants will tend to head toward the exit they are most familiar as they believe it will lead them to the outside and hence to safety. This is due to the occupant being acquainted with the geography of the route and being unsure with the geography of the escape pathway of an unfamiliar emergency exit. This behaviour means that purposely designed fire emergency escape routes are less likely to be used, defeating their purpose, assuming that they are not used normally. The familiar exits are normally the main entrance/exit to a building and are referred to as the "everyday exit" and do not include purposely made emergency exits. However, these exits are often over-looked by occupants as they may be reluctant to use them just in case they are locked or do not lead them to a safe area within the building. Hence, emergency exits are normally used by occupants who are familiar with the building layout with the choice of exit counteracted by good staff training in the event of an emergency

The choice of exit and the decisions made during the movement phase are often conducted under various levels of stress. It is the behaviour of the occupants under stress that can be very influential in judging the success of the evacuation. The major behaviours displayed during the movement phase in an evacuation include group affiliation/formation of the occupants, familiarity of the building, and the effect of panic or stress [18].

Group affiliation/formation can be either helpful or harmful during an evacuation based upon the decisions made by the occupants during an emergency. Group affiliation is defined as a group of occupants that are bound together by common social standing or interest. During an egress situation occupants may decide upon the action of evacuating once they have found all members of their group, which can include family members, friends and work colleagues. The time taken to wait or search for occupants in the worst case scenario may lead to the condition within the building becoming hazardous, leading to the occupants being trapped, unconscious or perishing in the fire.

Group formation and social affliction are important as it allows for occupants to communicate and process the cues with greater ease than if they were in the situation by themselves. The speed of communication within a group is very important and, as such, groups who are familiar with each other may communicate information more readily than strangers. People will often seek information about the risk of the situation and the reliability of the alarm to ensure that it is not a false alarm (discussed above), hence, the formation of a group is a highly desirable solution.

Unfortunately, present building regulations assume that occupants will head towards the nearest exit. Many post-disaster investigations and research studies have shown that in fact other exits are used. It is the familiarity of the occupants with the exits within the building that can significantly affect an evacuation and is often dominated by the familiarity behaviour complex.

Horiuchi [19] stated in conclusion to his studies on exit choice that "*the choice of an evacuation route will often be a regularly used route if the evacuee is familiar with the building. For those not familiar, following or relying on others is the norm. If familiar with the building, occupants have little difficulty finding exits even in heavy smoke. If the location of the stairs is not known, finding an exit can be of great difficulty. In all phases of the evacuation process, familiarity* *with the building was found to be the primary determinant of speed and ease of evacuation*".

3.3 Education and training

The majority of people will never experience an actual real life fire emergency, which is why it is important that each person has had some education and training on the processes that occur during an evacuation. Education and training normally starts at a young age at school and is continued into adulthood with compulsory training for staff members. The effects of training and education will be present within the long-term memory of an occupant and it is this memory that will be "called upon" during an evacuation. How the memory interacts with the decision process is shown within Figure 18 which illustrates how the cues and occupant based factors also influence the memory of an occupant [20].

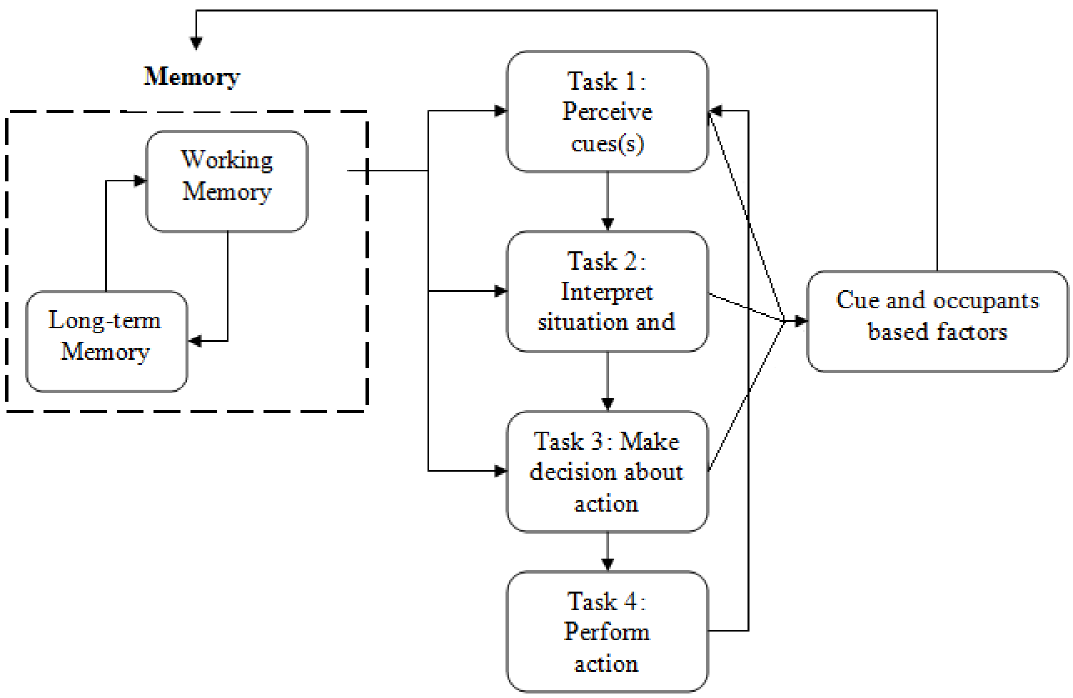


Figure 18: Training and Education Effect Model [20]

An example of the training provided at an educational establishment is that conducted by the school within the area of Tower Hamlets, London. Training is required to be held during the first term [21] so that all new entrants (pupils, staff or support staff) are inducted together and are shown the location of the fire escapes and fire exits, while all staff members are required to read a copy of the school written fire evacuation procedure/fire emergency plan with regular refresher training of the basics. The drills are required to be held every six months with a simulated situation where one of the fire escape routes is not available for use.

The lessons learnt at school are meant to stay with the occupants throughout adulthood, however, retraining and reinforcement of evacuation education is continued through the working career, which is further re-enforced by building-specific training. Further education may be required for staff members who are considered to be in a roll of authority (for example a fire warden) and it will be their job to help facilitate evacuation and ensure it is efficient and without problems. The use of a fire emergency evacuation plan (FEEP) is a common procedure in an office/business today. The FEEP is a written document which includes the action to be taken by all staff in the event of a fire, the arrangements for calling the fire brigade and an escape plan showing all exits and escape routes. The training should include the action to take when discovering a fire, the action on hearing the fire alarm, identification of key escape routes, location of fire-fighting equipment, etc. This is why numerous fire drills are important to provide occupants with a chance to simulate how evacuation during a fire would "feel" and what tasks need to be conducted.

Fire drills are intended to ensure that in the event of fire people who may be in danger act in a calm and orderly manner, people who may have designated responsibilities carry out their tasks to ensure the safety of all concerned, escape routes are used in accordance with a predetermined and practised plan, evacuation of the building is achieved in a speedy and orderly manner and an attitude is promoted whereby people react rationally when confronted with a fire. The main point of having fire drills is to provide training to the occupants of the key emergency procedures so that they become dominant and easily retrieved habits from long-term memory when required, in the event of a real fire.

Excessive training, testing of alarms and evacuation drills can have a negative impact on the effectiveness of an evacuation. It is customary for the fire alarms to be tested weekly within a building to ensure the system is in full working order. These tests often involve sounding the alarm for a set time interval, normally between 10 to 20 seconds, at a designated time of day. Along with these tests building authorities will undertake evacuation drills biannually, which are used to determine if the occupants evacuate the building within the desired design evacuation time. Often the occupants are aware of the time and date of the fire drill a week or two before it occurs (i.e. drills are announced). The noise of an alarm is meant to warn an occupant and gain their attention; however, occupants will wait, on average, 10 – 20 seconds to see if the alarms stop before starting to think whether or not the alarm is for an actual fire. If the alarm continues past the testing time occupants will start to ask questions about if the alarms legitimacy of if it is just a fire drill. This behaviour often requires a person with authority to intervene and provide information to the occupants to facilitate evacuation. The behaviours that occupants show before and during an evacuation can significantly affect how smooth and efficient the overall evacuation process is from a building , as seen in the evacuation studies held by Lund University [22].

3.4 Factors that influence performance

As discussed above, training and education of occupants is important in order to help facilitate an evacuation, yet it can also be detrimental due to the behaviours shown in section 3.2. Training does play an important role in behaviour during movement (not only during the pre-movement behaviour) as it may determine the exit choice of the occupants and increase the familiarity with the building. Occupants who also appear confident during an evacuation will inspire other occupants to follow them towards an exit, overruling the urge to evacuate through the exit through which they entered the building. The most influential factor on an occupant's movement behaviour (also during the pre-movement behaviour) is past experiences during evacuations.

As discussed by Proulx (see section 3.1), stress plays a significant effect on the decisions of the occupants both during the pre-movement and movement behaviour of an evacuation [15]. Stress can cause the occupants to feel anxiety, uncertainty and confusion and yet it is a necessity during any evacuation situation as it prompts the occupants into taking action when required. The feeling of not being in control or uncertainty leads to an investigation of the available cues and then the evacuation process, however, if there is no level of stress, occupants may be reluctant to leave the building (as previously outlined).

The concept of stress, as discussed by Stall [23], can be expressed in the context of the effects of stressors to the information processing. The stressor can include such influences as noise, vibration, heat, dim lighting etc., as well as such psychological factors as anxiety, fatigue, frustration, and anger. The effect of the stressors may be indirect or direct, where the direct effects influence the quality of information received by the occupant or how they perceive the response. For example, vibrations will reduce the quality of visual cues and noise will do the same for the auditory cues. Stress associated with time may simply occur due to the occupant thinking they do not have enough time to perceive information available, degrading their decision-making abilities. However, some of the stressors (like noise or vibration) as well as others for which no direct effect can be observed (like anxiety, fear, or incentives) appear to influence the efficiency of information processing by causing the occupant greater situational awareness [24].

Stress affects the decision-making process by reducing the occupant's ability to make rational choices when necessary. Yet, it is often difficult to know if a real-world decision that failed was in fact a poor one in foresight as well as in hindsight. Furthermore, it is often difficult to tell if it was the stress that was the factor which caused poor judgement or whether the conditions during the evacuation caused the error. Unfortunately, there is not a lot of information available about the effect of stress during real evacuations nor the appropriate techniques to help reduce its effects. It is very difficult to conduct research in this area as it would involve imposing realistic credible stressors in a controlled setting while still following the ethical code of research. There are negative effects of stress (fear, worry, etc.) the majority of occupants will describe this feeling as panic, which is often incorrect.

`Panic' is defined as sudden uncontrollable fear or anxiety, often causing widely unthinking behaviour. This widely unthinking behaviour can be detrimental to an evacuation if it occurs and it was believed for a long time that panic was a common behaviour during an evacuation. Most of the later studies showed that panic seemed to be the exception rather than the rule in evacuations. The sense of self-preservation at all costs can be observed during an evacuation and it is characterised by non-social behaviour, for example, pushing other occupants out of the way during an evacuation.

It is often during the post-emergency interview that occupants tend to start off by saying they felt panicked and unsure what to do. After this initial statement the person starts to describe the choices they made during the evacuation which often involve waking other occupants, calling the fire brigade and evacuating, apparently dominated by rational thought and with no real evidence of true panic.

In the original definition of panic it states unthinking behaviour; however, as seen from the evidence above, occupants who believed they panicked do some thinking behaviours yet are convinced they panicked throughout the evacuation. It is the feelings of fear and anxiety that people often mistake for panic when it is due to the stress of the situation.

3.5 Impact of information

The effectiveness of an emergency response during an incident is often affected by the lack of information provided about the current conditions. Deaths in large-scale fires are likely to have been caused by delays in the occupants receiving relevant information on the fire and egress routes [25]; this is why pre-movement behaviour is believed to be more important to survival than the actual movement speed [26].

The failure of an evacuation is often caused by providing the occupants with incorrect or insufficient information [27]. This leads to the occupants becoming overwhelmed by the effects caused by stress, as discussed above, reducing their ability to produce rational thoughts and corresponding actions. Therefore, it is very important to provide correct and easy to understand information during the pre-movement phase to reduce stress.

However, as discussed within Chapter 1, information has a significant influence on the decision making process and as stated by Wickens and Hollands [20] there is a fine line between providing enough information to help the occupants and providing too much information. If too much is provided it may lead to the confusion of the occupant, as they will not know what information they require or how it will help them, leading to an increase in stress, which is detrimental to the purpose of the providing the information in the first place.

3.6 Supporting Data

Before developing the Information Driven Evacuation System further it is important to discuss the supporting data that demonstrates that such a system is plausible. Hence within Table 2 are the behaviours that have been demonstrated during experiments and real-scenarios that validate the plausibility of the system.

Behaviour	Why it is important?
Group formation	Group formation is the process of occupants binding to each other during an emergency due to a common social interest. During an evacuation it allows for occupant to discuss the situation and information provided and make a group decision on the best form of action to take. This behaviour has been demonstrated in both experiment and real-life scenarios [18], [20], [24] and indicates the occupants will discuss the information provided by the system in order to understand what is required. Hence, the system will rely on an occupant's ability to determine the approach action to take, which is influenced by other occupants in the same situation.
Sharing of information	The sharing of information is very important and can help prepare the occupants mentally to evacuate a situation that they are finding stressful and boost their confidence through the evacuation. As demonstrated, occupants within an emergency will often share information based on the cues they have received, i.e. the activation of an alarm or the presence of smoke, in order to determine whether or not an evacuation is required and the best

	action to undertake. The system will provide up-to-date information to the occupants and relies on them understanding the appropriate measures to take, hence, it is important them to share the cues that the system is trying to make them aware of. [3], [13], [29], [30]
“Following the leader”	The interaction with other occupants is very important, however, the role an occupant takes during the interaction is more significant in assuring an effective and efficient evacuation. “To become a leader or be led” is an important choice that must be made by each occupant before deciding to evacuate during an emergency. Occupants appear to be more willing to leave if a leader of some sort is present and urging them to escape [15], [18], [19]. Hence, if the system is able to influence a “leader” it will, in part, help to influence the others. However, in some situations a person of authority may not be available and the choice above will still be need to be made. In order for the system to work at least one of the occupants within the situation will need to decipher the information provided and became the leader.
Inquisitive Nature	The final positive behaviour is the general and inquisitive nature of occupants during a scenario [20]. The uncertainty of a situation triggers this behaviour in occupants and they react in a range of way that all lead back to them thinking something is not right. This feeling of something is out of the normal is the behaviour that will allow the way-finding information provided by the system to influence their behaviour. A change in the background noise (an alarm or announcement), or the aesthetics of a room (flashing lights) will grasp the attention of an occupant and they will have to investigate further [31]. Without this behaviour way-finding tools would not be able to achieve what is required within the system.

Table 2: Supporting data for plausibility of the I.D.E.S.

Of course, with positive behaviours there are also negative ones that the system will need to be able to discourage in order to be plausible and are discussed within Table 3 below.

Behaviour	Why it is important?
Route of Familiarity	It is recognised that the mind-sets of evacuating occupants frequently have the effect of leading them towards the more familiar exits, with confidence that those routes will eventually lead to a location of "safety" [27], [32]. This behaviour is not often considered during the design of an evacuation plan as there is a tendency to rely on the use of purposely designed egress routes, which often are not the familiar exits. It is the lack of information and noticeable distinguishing features that are provided about these purposely designed egress routes that may lead to them being ignored during an evacuation, increasing the potential loss of life. Hence, the system is to provide more information on these routes and use tools to create distinguishing features during an evacuation. Some research has been conducted into the possibility of detouring an occupant from taking the familiar route, but normally this is only conducted using a single way-finding tool [31]. Hence, further research is required.
Ignoring of Alarms	Most occupants have chosen to ignore an alarm as it may inconvenience them in some way or another, as witnessed in many real-life scenarios [5], or believe that it is false/an alarm test [13]. Hence, the system has to be able to provide the appropriate amount of information to the occupants to prevent them behaving in such a manor. It is proposed that the system will be tested outside of "normal" office hours to prevent occupants becoming over exposed to it. Also, the use of way-finding tools, that change based on the sensor

	data and prediction models, should be able to change the mind set of inconvenience to one of survival. However, this is not known yet and needs further research.
Group Affiliation [18]	Group affiliation can be either helpful or harmful during an evacuation based upon the decision made by the occupants during an emergency [25]. Group affiliation is defined as a group of occupants that are bound together by common social standing interest, etc. During an egress situation occupants may decide upon the action of evacuating once they have found all members of their group, which can include family members, friends and work colleagues. The time taken to wait or search for occupants in the worst case scenario may lead to the condition within the building becoming hazardous, leading to the occupants being trapped, unconscious or perishing in a fire. No significant research has been conducted on whether or it is possible to deter occupants from waiting for a member of a group in order to preserve their own safety, however, it has been witnessed within some real-life scenarios [30].

Table 3: Behaviour needed to be addressed for plausibility of the I.D.E.S.

As Table X and Table Y show, there are both behaviours that demonstrate the plausibility of information driven egress and behaviours that need to be overcome for the system to be successful.

The final sections of this chapter will describe three case studies that will look into the design and behavioural issues that can occur in three different scenarios as well as demonstrating how the proposed system would work in an ideal situation with full understanding of the occupants.

3.7 Case Study 1 - Station Club Fire

The first case study chosen to demonstrate the potential for the Information Driven Evacuation System during the evacuation of a public space and how it would work within a real life scenario is the tragic fire known as the "Station Nightclub Fire".

3.7.1 Background

On the 20th of February 2003 at 11:07 pm, a fire that took the lives of 100 people and injured 230 occurred at the Station Nightclub, West Warwick, Rhode Island, U.S.A. [28]. On the night of the fire, the club itself was over crowded with occupants due to the combination of the clubs owners frequently neglecting the capacity limits of the building and the additional occupants who turned up to the clubs organised glam metal and rock and roll themed show that night. The incident happened to be captured on film as a private investigator for the Council was filming the show to gather evidence for the club owners neglecting of the allowable capacity limits and decibel limits.

The fire itself was caused by the use of pyrotechnics that were set off by the tour manager of the evening's headlining band, which ignited the flammable sound insulation foam that was used to line the walls and ceiling surrounding the stage as part of the noise control solution. This material ignited within seconds of the pyrotechnics being set off and engulfed the entire club within 5 and a half minutes.

3.7.2 Design and Behavioural Issues

The club itself was provided with four means of escape, which were all designed to be used as part of the egress solution. As can be seen below in Figure 19, only one of the four exits was located near the points of ignition. Emergency lighting, signage and alarm bells were also provided as part of the fire engineering design.

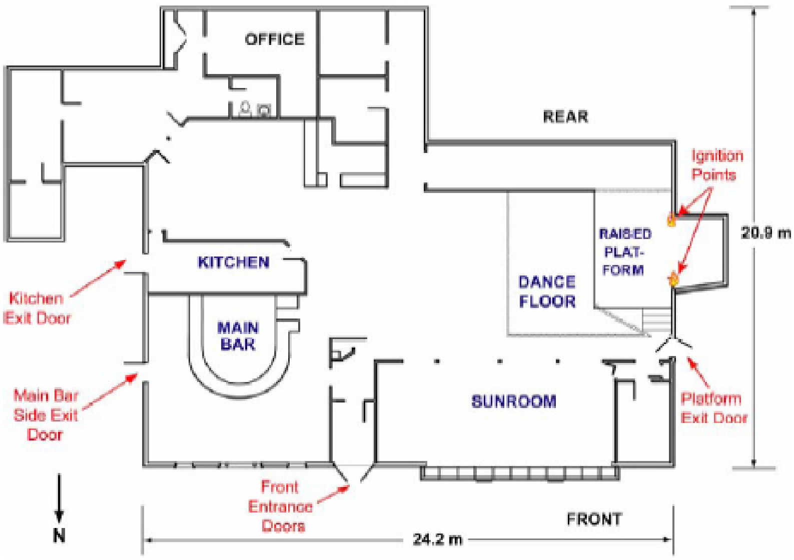


Figure 19: Station Club Site Plan [20]

The major design flaw of the club was not the egress routes, even though the main route did narrow to produce a bottle neck, but the use of highly flammable sound insulation foam set up which included a layer of highly flammable Polyurethane foam over polyethylene foam. The addition of the pyrotechnics created a strong ignition source that was able to set alight both of the foam layers within seconds.

The fire started within seconds of the activation of the pyrotechnics, however, it was first believed by the occupants watching the show to be a part of the stage performance. This was the first of the behavioural issues, as by the time people began to realise that it was an actual fire the flames had spread to the ceiling and thick black smoke began to billow out into the club. It fact the cameraman who filmed the incident stated that even when the flames started to hit the ceiling occupants just stood and watched it, with only some individuals backing off.

The second behavioural issue witnessed during the fire was the unfamiliarity of the occupants with the exit other than the main entrance, which was the most common exit. Some occupants tried using the exit at the back of the stage, yet they were turned away by the club bouncer as the exit was for the "band" only.

Another group of occupants went to use the main bar side exit door but turned away as underneath the exit sign was a hand written sign stating “Staff Only”.

The final behavioural issue was the most extreme of the behaviours witnessed, which was the stampede that occurred as the fire worsened. This led to occupants being crushed within the narrow hallway leading to the main exit and effectively blocking the exit completely.

It is possible to determine that the cause of the death was due to the use of an extremely flammable material and pyrotechnics within an enclosed space that was over its occupant capacity limit. However, it may have been possible to reduce the number of deaths and injuries within the building if the occupants were provided with more information at an earlier stage to reduce the pre-movement time and the associated undesirable behaviours. In addition to the extra information, the use of way-finding tools to help guide occupants to closer and available exits may have also reduced the number of fatalities.

3.7.3 Ideal Solution Using the I.D.E.S.

The following is a chronological breakdown of how the system could have worked as part of the evacuation solution for the fire if it had been installed within the club.

- Show starts with the ignition of the pyrotechnics

- Real-time sensor data is being analysed by the system for a change in the condition from the background information.

- Flammable foam ignites.

- Real-time sensor data acknowledges a change in the conditions and activates the server.

- Server activates the building alarm, the model prediction, and the information driven evacuation system. Fire service is alerted. All non-fire safety audio sources are deactivated.

At this point it should be noted that due to the intensity of the fire, the prediction model may not have been afforded enough time to provide the system with a prediction of the fire development and the occupant movements due to how fast the fire actually developed due to the material used for soundproofing.

- Information driven evacuation system activates the audio and visual tools installed within the building.

- Audio speaker announce to the occupants that there is a fire and to evacuate to the nearest exit.

- Using real-time sensor data evacuation prediction determines that occupants are mainly heading towards the main exit.

- Directional audio speakers are activated as well as green flashing lights to guide occupants towards the exit behind the stage, the exit within the kitchen and the exit to the side of the bar.

- Once the condition of the fire reaches a point where the exit behind the stage become unavailable the audio and visual systems change to direct occupants away from using that exit.

- Using real-time sensor data the evacuation prediction determines that one of the three available exit is underutilised. Audio message is changed over capacity exits to guide occupants to use the underutilised exit.

- Evacuation ends, system is shut down at the server.

The idea behind providing the occupants with up-to-date information is to reduce pre-movement time of the occupants and to eliminate the undesirable behaviours of the occupants idly standing by and watching the fire develop to a level that is extremely hazardous. It is also provided to reduce the level of stress experienced by the occupants with the goal of counteracting the stampeding behaviours witnessed during the real fire and to improve their rational decision making process as they evacuate the situation.

3.8 Case Studies 2 – 2008 Channel Tunnel Fire

The second case study chosen to demonstrate the potential for the Information Driven Evacuation System during an evacuation from a tunnel and how it would work within a real life scenario is the "2008 Channel Tunnel Fire".

3.8.1 Background

On the 11th of September 2008 at approximately 3:54 pm, a fire occurred upon a HGV (Heavy Goods Vehicles) shuttle that was carrying twenty-five lorries and two vans [29] . The train was traveling from the UK to France within the RTN (Running Tunnel North) and was also carrying thirty-two occupants. At 3:59 pm the train is stopped within the tunnel and the evacuation of the occupants was initiated. Even though there were no fatalities, of the thirty-two people on board the train at the time of the fire, fourteen people suffered minor injuries and were taken to hospital for treatment.

The official report into the fire [29] stated that the initial cause of the fire is still not exactly known, it was suspected that a road vehicle caught fire which spread to the whole of the rake. It was discovered that one of the vehicles on board the train had an electrical fault meaning it could not turn off its headlights and this vehicle so happened to be within the rake where the fire appeared to have started.

The Channel Tunnel forms the rail link between the UK and France and consists of three parallel tunnels (See Figure 20). Two of the tunnels are provided with a single rail track and are used by the trains to run in different directions. It is the third tunnel that is key for the evacuation design and has three safety functions:

- To provide normal ventilation for the other two tunnels
- A safe location for occupants in the event of an evacuation
- A speedy access route to be used by the emergency services.

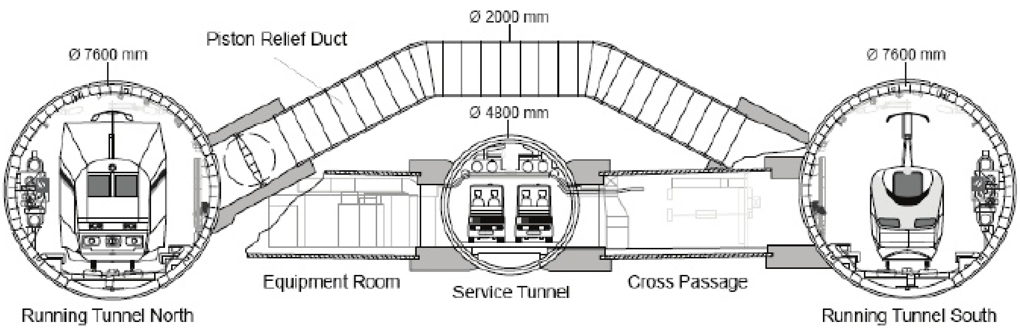


Figure 20: Channel Tunnel Cross-Section. [29]

All the tunnels are approximately 50 km long.

3.8.2 Design and Behavioural Issues

As stated above a service tunnel was provided as a safe location for occupants during an emergency evacuation and is accessible via cross passages located periodically along the length of the tunnel. As part of the evacuation design, the chef de train or train driver is meant to stop the train alongside one of these cross passages so that occupants can use the coaches' emergency exit to evacuate. In addition the ventilation system within the tunnel is meant to provide a flow of about 2.9 ms^{-1} in the opposite direction to the direction of train travel to blow smoke away from the occupants during the evacuation. However, a series of human and mechanical errors meant that the evacuation did not go as planned.

The first issue occurred within the amenity coach that was carrying the passengers. On the day of the fire, the egress door of the amenity coach was having mechanical issues before it was due to leave for France. One of the coaches' passenger doors was not closing properly and therefore was cable tied shut prior to departure as a quick fix solution and a sticker was placed over the doors stating "door isolated, do not use". Therefore, when the occupants came to use the door during the evacuation they could not get it open and had to use the other door, eventually some occupants resorted to breaking the window to use as an egress route. There were also communication difficulties between the train operator and the passengers which did not aid the situation.

The second issue occurred due to the driver whom, once warned about the fire due to the detection systems in place, attempted to continue to drive the train out of the tunnel. He finally chose to stop once he noticed a faulty system warning light. Due to lack of visibility within the tunnel he could not identify the location of the train and ended up stopping near marker PK49, which was located in the last third of the tunnel. The chosen stopping point of the train meant that the amenity coach door normally used during an evacuation was not opposite a cross-passage entrance.

The final issue occurred when the ventilation system was activated, which was delayed by 15 minutes while the nearest cross-passage door was being opened. On activation it soon became apparent that the fan blades were set incorrectly meaning there was no longitudinal flow within the tunnel for nearly 10 minutes. It was not until the longitudinal flow was established that the evacuation could start, a full 24 minutes after the train came to a halt within the tunnel.

The behaviour of the occupants during the incident was gathered during the completion of the Technical Investigation Report [29] and the following key behaviours/issues where identified. The Train operator followed procedure before departure and played a pre-recorded announcement in both English and French telling the passengers what to do in the event of a smoke alarm and about the use of the breathing masks.

After the alarm sounded the driver looks to the wagons and notices the fire himself, closing the ventilation dampers in the amenity coach and calls to a member of staff to get out the breathing masks. At this point the passengers have seen the fire and begin to move to the front of the coach, away from the fire, blocking the train operator from the rest of the staff.

The train operator informed the driver of the fire and suggested they needed to stop. The driver could not make contact with the control centre and eventually stopped the train. Once the train had stopped, the operators ensured that the train could not move any further. A member of the staff is gives the thumbs-up when she was asked if she could see a cross-passage, and on seeing this the train operator asked passengers to follow him, result in him opening the right-hand rear door where smoke initially began to flow through the amenity coach. Assuming everyone was following him, he headed towards the cross-passage where he found the passengers and the other members of staff waiting as they had left the train through a window which was broken by a passengers in order to evacuate.

The window was located near the front right-hand door, which was the door that was normally used for evacuation but on this service was tied shut due to mechanical issues. An occupant near this door grabbed a hammer and broke a nearby window as the smoke started to pour in from the other doors. Before evacuation a member staff noticed that four occupants had left via a left-hand door. These four passengers were unaccounted for by the train operator and could not be seen due to so much smoke within the tunnel. These passengers were later found by emergency services in pairs within the tunnel at the front of the train.

3.8.3 Ideal Solution Using the I.D.E.S.

The following is a step by step time line of the how the system would have worked as part of the evacuation solution for the fire if it had been installed within the tunnel and train.

- Train enters the Tunnel

- Real-time sensor data begins to be analysed by the system for a change in the condition from the background information.

The system would be installed within the tunnel and the train assessing both in real-time and when both system activate it is referred to as a positive detection activating the server. However, the activation of either the train or tunnel system sends a warning to an operator for early prevention.

- Road vehicle ignites.

- Real-time sensor data acknowledges a change in the conditions and activates the server.

- Server activates the tunnel / train alarms, the model prediction, and the information driven evacuation system. Emergency services, the Control centre and driver/train operator are alerted.

- Train driver begins the emergency stopping procedure and is advised via the prediction model the location where the train will stop allowing for adjustment for the location of the nearest cross-passage.

- Information driven evacuation system activates the audio and visual tools installed within the train and tunnel.

- An audio speaker announces to the occupants that there is a fire, to put on their breathing masks and to evacuate to the nearest exit.

- Server detects a failure of one of the egress doors and promptly adjusts audio and visual tools to deter occupants from trying to use the unavailable route.

- Directional Audio speakers are activated as well as green flashing lights to guide occupants towards the other available route within the train.

- Fire prediction model and server determines that the ventilation is not providing the longitudinal flow required and warns the operator and occupants.

- Audio and visual tools change to halt evacuation from the train while the ventilation is activated correctly.

- Once the ventilation is activated and the conditions within the tunnel are at the required level for evacuation the way-finding tool once again indicate the available exits.

- Audio and visual tools within the tunnel guide the occupants towards the cross-passage that is open for evacuation.

- Evacuation ends, system is shut down at the server.

The principle behind providing the occupants with up-to-date information is to reduce the confusion that occurred within the initial stages of the emergencies allowing for a more controlled and calm evacuation. It is also provided to help reduce the level of stress experienced by the occupants and allow them to discover the location of the working egress doors with the purpose of reducing the time they had to wait at the cross passage before entering the safety of the service tunnel.

3.9 Case Studies 3 – Cook County Administration Building Fire

The final case study chosen to demonstrate the potential for the Information Driven Evacuation System during an evacuation of a high rise office tower and how it would work within a real life scenario is known as the "Cook County Administration Building Fire".

3.9.1 Background

On the 17th of October 2003 at approximately 5:00 pm, a fire occurred within the 36 storey tall Cook County Administration Building [30]. The fire itself was located within Suite 1240 on the 12th floor of the building and lead to the death of 6 occupants and injured approximately a dozen other occupants.

The building was provided with two centralised stairwells that were accessible from each of the floors, however, once the occupants were within the stairwells it was not possible to gain re-entry to any floor or gain access to the roof. The building was also equipped with smoke and heat detectors, which were connected to the Fire Alarm Control Panel in the building's Lobby. There were no manual call points installed within the building except that on the Fire Alarm Control Panel and this was also the only location where a P.A. message could be broadcast about an incident.

The full occupant capacity of the building was cited as being nearly 2,000 occupants during office houses; however at the time of the fire it was significantly less at 250 occupants due to the fire occurring at around 5:00 pm on a Friday.

The fire was detected by a female employee, who was one of five people located in Suite 1240 on the 12th floor where the fire originated. She smelled smoke and raised her concerns amongst the other occupants before investigating the smell and discovering a fire within the storage room. By the time the occupant actually left the area of the fire, as they took time to secure file and money within the safe before leaving, the smoke was at head-level. During this time the security office within the Lobby heard an alarm coming from the alarm panel and advised a building engineer about the location of the fire. As the engineer unlocked the door from the stairwell to level 12 he was knocked down by a backdraught. It should be noted that when he unlocked the door it had only been 4 minutes since the initial occupant discovered the fire and, upon opening the door, the corridor he was in filled almost instantaneously with thick black smoke.

The first P.A. message, as requested by the engineer on the 12th, who had also called 911, was announced at 5:03:15 pm telling occupants to "Evacuate the 12th

floor". The second P.A. message given told occupants on the two floors above and five floors below level 12 to evacuate. Almost immediately after the second message a third was given at 5:05:05 pm advising all occupants to evacuate the entire building. However, prior to the third message all occupants were evacuating the building via the elevator and not the stairs. Hence, the third message also told occupants to evacuate the building by using the stairs and not the elevators.

The Chicago Fire Department arrived minutes later and began to fight the fire from the South-east stairwell but they initially were unable to advance further than the stairwell door due to intense heat and large quantity of thick smoke.

The human behaviour study completed by the NRC (National Research Council Canada) [30] concluded that the loss of life in the fire was mainly due to combination of three factors that if they were to occur individually would have most likely not led to loss of life.

3.9.2 Design and Behavioural Issues

As stated above, the building was provided with heat and smoke detection that connected to a central panel within the lobby of the building. However, there were no manual alarms installed within the building and this meant that the only person who could raise the alarm was a security office at the panel. This was the first design issue within the building. On seeing the fire, the occupant had to leave the 12^{th} floor and travel down to the first lobby before she had the ability to warn staff of the fire. Even though the automatic system had detected the fire before she warned the security staff, she could have alerted the staff approximately 3 minutes earlier which is a significant amount of time to allow the fire to develop before an evacuation is initiated.

The delay of initiating an alarm was also increased due to the poorly designed security procedures in place within the building. On detection of the fire, the fire service was not called nor were the occupants warned to evacuate but instead the building engineer went to investigate the alarm. By the time he got to level 12, via the stairwell, the fire had developed to such a level that the floor was enveloped in thick black smoke. Only after seeing this was 911 called and the evacuation of level 12 announced on the P.A.

The initial evacuation of only level 12 was also an evacuation plan design error. On seeing the amount of smoke a building wide evacuation should have been announced. However, this error was quickly fixed and the message was changed on the P.A. system for a full building evacuation and this message was repeated every 15 seconds over a period of 2 hours. The NRC considered this to be one of the three failures that led to the fatalities.

It should be noted that all occupants who worked within the building were provided with training on the proper evacuation procedure to take in case of an emergency, with trial evacuation annually conducted in the building. However, a counter-intuitive behaviour that occurred in the initial stages of the fire was for the occupants to gather all their personal items and make sure that money and private documents were secure and locked away before evacuating. This meant significant delays leading to rather more significant pre-evacuation time that predicted model had not designed for. Once the occupants had finally started to evacuate they chose to use the elevators instead of one of the two stairwells available, even though they had been trained to. It was not until they were advised to via a P.A. message did the occupant's use the stairwell. This demonstrated the occupant's instinct to exit the building via the most familiar route, which in this case was via the elevator. It also demonstrated the "following the leader" behaviour discussed within this chapter, where occupants would use an elevator after seeing other occupants waiting in the lift lobbies.

The second of the factors identified by the NRC was the activities of the fire fighters who attended the fire. After arriving on site and being notified of the fire location on level 12 they fire fighters took the elevators to the 9th floor and walked up the South-east stairwell. Once they had connected a hose line into the building's hydrant system on the 9th and 11th floor they began to advance by the stairwell to fight the fire. However, due to the vast amount of heat and smoke being produced by the fire they were not able to advance further than the door from the stairwell. The activity of the fire fighters that was considered to be the second behaviour occurred as they advanced to the 12th floor. An unknown number of occupants, once they were told to, began evacuating the building via the southeast stairwell. Some of these occupants stated that they saw no smoke or only light smoke was present within the stairwell, yet as they moved down the smoke became heavier. On making to the 12th floor, some occupants report that they were told by fighters preparing to attack the fire to go back up the stairwell and evacuate using the North-west stairwell. This, in combination with the third factor, lead to the death of 6 occupants.

On being advised this, occupants began to go back the way they came and travelled upwards in the stairwell. However, the building had been design so that once an occupant was within the stairwell the door they used to gain access would be locked so re-entry was not possible nor was access to the roof. Even when the buildings alarm had activated the door still did not unlock and required one of two master keys to gain access, even during a power failure. Therefore, as the doors were all locked it was not until an occupant had reached the 27th floor before an unlocked door was discovered. The locking feature of the doors was the third and final issue identified by the NRC. Even though some occupants were able to get to the open door and transfer to the North-west stairwell most were overcome by thick black smoke and were unable to continue their evacuation. Some of the occupants survived the smoke filled stairwell by laying down with their faces near the cracks of the doors in an attempt to breathe clean air from the unaffected floors.

The fire was finally extinguished at approximately 6:40 pm, an hour and forty minutes after it was discovered by an occupant.

3.9.3 Ideal Solution Using the I.D.E.S.

The following is a step by step time line of the how the system would have worked as part of the evacuation solution for the fire if it had been installed within the building.

- Real-time sensor data is running constantly by the system analysing for a change in the condition from the background information.

- Occupant notices smell and goes to investigate.

- Sensor data notes a change in the condition and activates the server and sets off alarm on panel waiting for system initiation from a member of staff.

- Occupant activates the manual alarm, server recognises the manual alarm and activates the building alarm, the model prediction, and the information driven evacuation system. Fire service is alerted.

Note: as part of the system installation a manual system will be provided in the building to provide a secondary confirmation of the fire so that the server can initiate an evacuation without having to have the building engineer investigate.

- Building evacuation scheme is designed as a staged evacuation, therefore system only evacuates the affected floor.

- Information driven evacuation system activates the audio and visual tools installed upon the 12th floor.
- Audio speaker announces to the occupants that there is a fire and to evacuate to the nearest exit.
- Using real-time sensor data evacuation prediction determines that occupants are waiting to use the elevators. Speakers in lift lobby tell occupants to use the stairwells.
- Directional audio speakers are activated as well as green flashing lights to guide occupants towards the available stairwells.
- Sensor-data and fire model predicts fire development will require the building to be evacuated. Building wide evacuation announced.
- Directional audio speakers are activated as well as green flashing lights to guide occupants towards the available stairwells on remaining levels.
- Fire fighters begin to fight the fire via the South-east stairwell.
- Sensor-data and fire model predicted large building up of smoke within the South-east stair.
- I.D.E.S. changes audio speakers and lights to guide occupants away from the South-east and towards the North-west stairwell.
- Systems above South-east message changed to the exit unavailable message as well as the exit sign and lights to red lights.

- Systems above North-west message changed to the exit available please exit this way message as well as the exit sign and lights to green lights.

- System notes locations of trapped occupants and the fire on panel for the fire service information.

- Evacuation ends, system is shut down at the server.

The ideal use of the system would be able to provide an early warning about the fire so that an evacuation can be initiated before the conditions become hazardous as well as providing the occupants with up-to-date information on the development of a fire so that they can safely evacuate the building using the egress route that is not affected by smoke. It would be used to counteract the use of the elevators in the building and reduce the amount of time the fire is allowed to develop before the fire service arrives.

3.10 Summary

In summary, the chapter above discusses the effect of an occupant's behaviour on the decision-making process and the influence of factors, such as stress, on the clarity of the decisions made. As well as how the three primary phases for an evacuation process; perception – interpretation – action, can be affected by external and internal factors, e.g. smoke and pre-movement activities, and the behaviours that can be helpful or detrimental (e.g. group affiliation and returning to an exit of familiarity) to the success of an evacuation. It also showed that providing occupants with information on the situation during evacuation can be both a positive and a negative tool based on the amount of information and how it is provided.

As part of the development of the Information Driven Evacuation System, the behaviours of occupants that have been demonstrated within both experiments conducted by researchers and information gathered from real life scenarios has been taken into account. Following this, three case studies were analysed to demonstrate the issues that occurred and how the installation of the I.D.E.S. would work in an ideal situation. However, the I.D.E.S. described within the case studies relied heavily on the existing fire safety precautions installed within the building and attempted to utilise the evacuation routes. These precautions and routes are designed based on procedural measures and design codes that must be followed by an engineer and these will be discussed in the next chapter.

4 Procedural Measures / Design Code Requirements

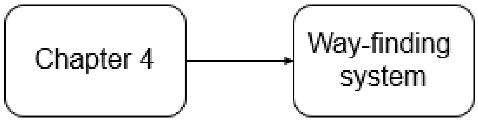


Figure 21: Topics covered within Chapter 4 compared to the system.

The underlying objective of an evacuation design is to ensure that in the event of a fire, occupants within the building can reach a place of safety (a location unaffected by the fire, generally outside the building) without relying on external assistance from rescue services [33]. Engineers are provided with two types of design approaches to use as a basis to fulfil these requirements. These have been developed based on research conducted or from the analysis of real-life events. Yet, it is not possible to predict every possible scenario that could occur, especially when concerning a fire and the reaction of the occupants.

As seen within Figure 21 above, this chapter will cover how the requirements of the design approaches will influence the type of way-finding systems available within a building to use as part of the I.D.E.S. and the additional systems that need to be provided. Hence, the first discussion within this chapter will be on the background and requirements of the two types of design solutions currently used in practise.

4.1 Design approaches

The design of an egress solution can follow one of two basic approaches that are known as prescriptive and performance based. A prescriptive code sets a series of design limits that an engineer is required to meet as part of the egress solution. An example for a prescriptive code may specify the number and capacity of egress routes required within a building, based on the design occupant load determined from the architectural plans. A performance code is a goal-based approach which provides an engineer with a greater freedom to apply judgement to an egress design; under this methodology a solution may be considered acceptable providing sufficient evidence is shown that the concept will work, and safety targets will be achievable, typically through the use of models/simulations and/or hand calculations.

Within England, the requirements of the Building Regulations are stated, and approaches to meeting them expanded, in the Approved Document B on "Fire Safety". This framework provides many links to other standards, which historically where mainly British Standards (BS) but now include more European and international codes. The British Standards themselves are a large set of documents but they include a number of standards relevant to life safety during egress and emergency evacuation. The underlying aim of the documents is to provide the occupants with enough time to escape to a place of relative safety before the conditions reach the tenability limits, which are not often defined within the standards. This requires the designer to take into account the time to detect a fire and sound an alarm, occupants' pre-movement time which consists of the recognition time and the response time, the travel time (including queuing) to a place of relative safety and the movement within a place of relative safety (e.g. protected stairs or compartments). The objective is to limit the time taken to travel through areas within a building that could potentially be exposed to fire and smoke. There are two primary stages that occur before an occupant starts to evacuate, which are the time to alarm and the pre-movement time. All of these factors can in principle be accommodated by performance-based approaches to egress design, as expounded in BS7974 part 6, though many issues are left open-ended in this design methodology, i.e. the user to supply relevant design parameters from external sources or trials.

There are certain requirements that are present within both kinds of design codes, for example; the installation of an alarm to warn occupants, the requirement to provide a "safe" route during an evacuation and a means of communicating to occupants on the routes within the building. Hence, the following sections will discuss the common requirements, the design requirements and process needed for these to be successful during an evacuation.

4.2 Breakdown of evacuation time

The fundamental design principle of any evacuation plan is to ensure that if an occupant was to find themselves within a dangerous situation, i.e. a fire within a building, the design of the building and the fire safety equipment can afford them enough time to exit the situation before being overcome by hazardous conditions. However, there within certain design codes [33] are lists of design criteria an engineering must met, i.e. the prescribe maximum travel distances (the allowable design distance an individual can travel in an area which is not "protected") or minimum exit widths, but often make no mention of the *time* required for an occupant to escape [34], [35],[36]. In reality the escape process of an occupant evolves over time, as such, an engineer using the performance based design approach is given a series of basic principles that can be used to determine the sufficiency of an evacuation design. The designer must demonstrate that the estimated time available before the conditions within the building become hazardous affords the occupant enough time to evacuate to a safe place without being overcome by the conditions. These times are often referred to as the available safe egress time (ASET) and the required safe egress time (RSET) and the sufficient condition can be expressed as ASET >> RSET.

A visual representation is provided in Figure 22 and shows that the difference between the ASET and RSET is a factor known simply as the Margin of Safety. The ASET is determined based on tenability limits that are provided within the design codes and includes such factors as visibility and the Fractional Effective Dose of carbon monoxide. The ASET is determined either using formulas (simple projects) or computer modelling programmes (complex projects) and provides an engineer with a upper time limit they must adhere to during the evacuation design phase. The focus is on the design process to ensure that the RSET is less than the ASET, with some sort of margin of safety also provided. The RSET is measured from ignition and in total incorporates the time to detection, time from detection to the raising of an alarm, the pre-movement time of the occupants, and the time it takes for the occupants to travel through the building to a safe place.

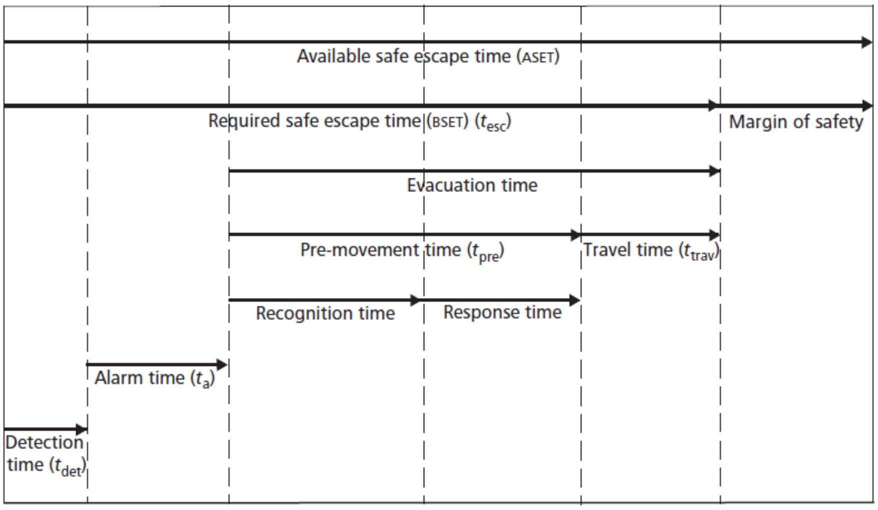


Figure 22: visual break down of the general approach to evacuation times [36].

The detection time and alarm time are determined based on equations and limits that are associated with the type of detection system used in the building. Normally detection and alarm time are not a significant factor compared to the pre-movement time and travel time, which added together equal the total evacuation time.

The pre-movement time and travel time may be expressed as distribution of times for the population or approximated by a single value that represents the whole population. However, this is a gross over simplification of the pre-evacuation behaviours of the occupants and as discussed within Chapter 3 it can often be misinterpreted.

4.3 Pre-movement (e.g. time to respond)

Pre-movement time is the combination of the behaviours and processes that occupants will go through once an alarm has been sounded until they begin to evacuate the building. The actions of the occupants within the evacuation scenario are not consistent between different scenarios and may result in significant time delays. There are many factors that can significantly affect the pre-movement time as discussed within Chapter 3, this section will look into the design codes' process of calculating the pre-movement times.

Pre-movement times may be approximated by taking nominal values for different cases as per the example below in Figure 23, though these are often rather large and generally conservative. For example, the pre-movement time recommended for a hotel is 30 minutes, which seems generous. The reason it is this large is because it is unknown how quickly a person will react to the alarm when they have just been woken up or how reluctant they will be to react to an alarm when disturbed from sleep, considering the possibility that it might be a false alarm and they evacuate for no reason.

Occupancy type	Pre-movement time / min
Residential:	
— hotel bedrooms	30
— university hall of residence	20
— residential college	20
Education:	
— school	3
— nursery school	3
— university/college	3
— adult training centre	3
Offices:	
— office	1
— bank, building society, post office	2

Figure 23: Suggested pre-movement times [35]

Another approach the codes use to calculate pre-movement time is to adopt approximate distribution patterns determined from research studies (e.g. Figure 24). However, there is a lack of data on pre-movement time for many different scenarios and hence the ranges of possible behaviours are difficult to measure. The major problem when trying to quantify pre-movement times into a standard value that can be used for every type of fire scenario is that it is very dependent upon the occupancy type, the nature of the warning system and implementation of the emergency management procedures.

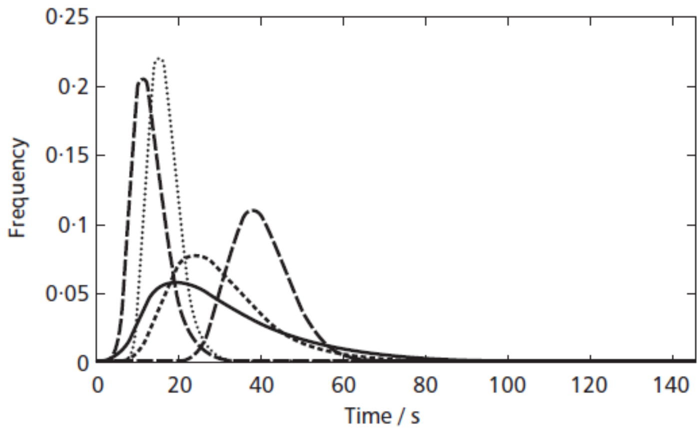


Figure 24: Mathematical distribution patterns for pre-movement time [35]

The total pre-movement time is a large proportion of the total evacuation time, however, it is not appropriate to simply add the total pre-movement and total travel times together to calculate the total evacuation time, these will often provide an overly conservative value. The general over-estimation of the pre-movement times can be credited to the lack of information available on pre-movement behaviours as current recommended code values are derived from experimental research that does not effectively simulate a real life fire.

This simplification of a complex process is one of the major reasons why an evacuation design fails and led to the development of this thesis topic and the I.D.E.S.

4.4 Evacuation movement

The other essential time that forms part of the total evacuation time is the travel/movement time of the occupants which is described as the movement time required to reach and pass through an exit into an area of safety. The calculation of travel time is determined by the number and distribution of occupants, the speed of travel towards an exit and the flow rate through restrictions (doors, stair, etc.). Travel time calculations do not rely on the pre-movement behaviours of the occupants and hence the calculations are evaluated as if the occupants were to react immediately and appropriately to a warning of a fire. The calculation is an indicator for the designer whether the travel distance or the width of the egress route is the limiting factor determining the travel time.

The movement of occupants through a building is divided into two sections; horizontal or vertical means of escape, with each section breaking down the necessary requirements and factors that affect the travel time. Horizontal movement deals with the provisions of means of escape from any point within a storey to the next storey exit of the floor. Hence, horizontal movement is determined by the number of occupants, the layout/number of escape routes and exits, the travel distance, and the width of doors, corridors and escape routes.

The number of the occupants within the building is determined by either the maximum number of persons the building is designed to hold or the number calculated by dividing the areas of room or storey(s) by the appropriate floor space factor. The overall capacity of the building should be determined by the capacity limit of the stairs rather than using the floor plate of a building as this can often result in an overestimation of the occupancy number. Possibly resulting in a situation where there may not be sufficient egress routes available to evacuate the building during an emergency.

It is unknown whether or not all exits within the building will be able to be used by the occupants if a fire occurs, as an escape route can be rendered unusable by fire, smoke or fumes. Hence, design codes often require that at least two alternative escapes routes be provided from every storey or floor level [35]. The number of exits on the horizontal plan is determined by the number of intended occupants and a table of the number of exits the code requires (Figure 25). Once the required number of exits needed within the building is calculated, the code provides information on the layout of the exits depending on different circumstances.

Minimum number of escape routes and exits from a room, tier or storey

Maximum number of persons	Minimum number of escape routes/exits
60	1
600	2
More than 600	3

Figure 25: Minimum number of escape routes and exits required [35]

The maximum allowable distance which an occupant should travel within the building is often determined by a set of standard values within the code. The table (Figure 26) shows the values required by BS 9999 (2008), which are derived from the time available to travel safely to an exit and the risk profile of the building. Each risk profile takes into account the fire growth rates, the familiarity of an occupant with a building, the addition of extra fire protection measures, an occupant not going directly to an exit, speed of the occupants based upon their characteristics and how the pre-movement times will vary with the room size, the occupant characteristics and the management provision.

Risk profile	Travel distance, in metres (m)	
	Two-way travel	One-way travel
A1	65	26
A2	55	22
A3	45	18
A4 B)	Not applicable B)	Not applicable B)

Figure 26: Maximum allowable travel distance [35]

The widths of the doors, corridors and escape routes within a building are also determined by the risk profile stated above and are shown in the table below.

Risk profile	Minimum door width per person mm
A1	3.3
A2	3.6
A3	4.6
A4 A)	Not applicable A)

Figure 27: Required widths of doors, corridors and escape routes [35]

In the case of a scenario where one of the exits within a storey becomes unusable due to fire, the remaining exits need to be wide enough to allow all the occupants to leave quickly. Thus, it is normal practice for designers to determine the egress solution for a building by assuming the largest of the exits is unusable. In evacuations where the storey is crowded the travel distance becomes less important and the queuing behaviours and door capacities become the critical feature of the horizontal design.

The vertical means of escape involves the transition from horizontal escape from the building to a place of safety (i.e. a protected stairwell, or outside the building). Hence, the vertical design must meet the performance recommendation of the horizontal design for each storey exit within the building. The most common form of a vertical egress solution is the use of a stairwell.

When designing a stairwell for vertical egress it is important to make the stairs wide enough so that the desired flow rate can be achieved. However, stairwells are often accessed by all the horizontal exits simultaneously and all occupants will exit towards the final exit at the bottom of the stairs. As such, the stairs may become congested leading to occupants being unable to leave their individual floors. This factor is taken into account within the codes for recommended widths of escape stairs. In a building where two or more stair stairwells are installed it should be assumed that one of them might not be accessible due to smoke or fire [34]. Therefore, during the design phase it is necessary to discount each stairwell in turn in order to ensure that the capacity of the remaining stairs are adequate for the number of occupants within the building. The occupancy characteristics and the risk profile of the proposed building will determine the minimum width of the stairs (Figure 28 and Figure 29).

Occupancy characteristic	Width of stair for downward travel	Width of stair for upward travel
A	1 000	1 200
B (except assembly)	1 000	1 200
B (assembly only)	1 100	1 200
C	1 000	1 200

Figure 28: Minimum width of stairs [35]

Risk profile	1 floor	2 floors	3 floors	4 floors	5 floors	6 floors	7 floors	8 floors	9 floors	10+ floors
A1	3.90	3.40	2.95	2.45	2.15	2.00	1.80	1.70	1.50	1.40
A2	4.50	3.80	3.25	2.75	2.45	2.20	2.00	1.90	1.70	1.60
A3	5.40	4.60	4.00	3.50	3.10	2.80	2.60	2.30	2.10	2.00
A4 [A)]	—	—	—	—	—	—	—	—	—	—

Figure 29: Minimum width of stair per person [35]

Movement time is greatly influenced by the number of occupants within the building, the overall mean walking speed and the exit they choose to use. The exit choice will determine the level of queuing within the building, which in turn will either increase of decrease the movement time. Queuing times are also

determined in the codes using an evacuation and vary depending on the code used.
As stated above, it is unknown whether or not all exits within the building will be used by the occupants and as discussed within Chapter 3 an occupant may not even be aware of the existing routes. The goal of the I.D.E.S. is to guide occupants towards the available routes within a building in order to improve the efficiency of an evacuation plan while significantly improving the chance of exiting the affected area without being objected to hazardous conditions. However, in order to be able to do this the system requires the use of a combination of visual and audio way-finding tools.

Even though the code provides information on how to design a building to ensure the overall evacuation time is as efficient as possible, there are evacuation tools which are used within a building to help facilitate an evacuation.

Audio and visual tools are already in use through evacuation designs, yet the majority of buildings only ever installed the bare minimum required by law based on the design codes. The following sections discuss the bare minimum requirements need to satisfy the audio and visual requirements of the codes.

4.5 Audio

The purpose of an audio alarm is to warn occupants within, or near, a building of the occurrence of an emergency scenario in order to enable those occupants to take appropriate measures. The audio proportion of an evacuation alarm system is based upon the design of the overall fire alarm system within a building, with codes recommending how to plan, design, install, use and maintain the system.

4.5.1 Audible Alarm with Sounders only

It is essential that any alarm signals used are sufficient enough to provide a warning to all occupants to whom the alarm signals are intended. In most buildings the alarm produced needs to be able to alert all occupants regardless of their location. As the complexity of the building increases, e.g. in a hospital, a general audible alarm type may not be appropriate. However, even though a lot of information on the process design is provided within a code, there are over 25 codes alone in the UK that describe the design process of a specific alarm system.

The majority of buildings will be provided with an audible alarm that will normally only incorporate sounders or a bell. The minimum requirement of the specific code [37] is that the sound level provided must produce a fire alarm signal immediately audible above any ambient noise. Yet there is also a limit set by the code in order to avoid damage to an occupant's hearing. The sound levels of the alarm are required to have a minimum level of 65 db above any other noise that is likely to persist for a period longer than 30s unless that alarm is intended to wake up sleeping occupants then the minimum level should be 75 db above any other noise that is sounded for longer than 30s [38]. The sound used by the alarm must be consistent throughout all parts of the building and all electronic sounders must have a standard tone. The alarm signals are required to continue, once activated, until they are manually turned off at the alarm panel by a person of authority.

So it can be seen that, even for a simple alarm there is still a significant amount of design requirements that must be met for it to comply with the standards, with the requirements becoming even more onerous with increasing complexity of the system. Two example of audio way-finding tool are as Voice alarms and Directional audio.

4.5.2 Voice alarm systems

Voice alarm systems are an effective means of warning and evacuating occupants while supporting the designated fire safety strategy and often are better at initiating an evacuation than just a standard alarm bell. Before the system is designed, a risk assessment of a fire occurring within the building must be conducted in order to determine the required type of voice alarm system needed [39].

Of course, as well as alarm bells, there are more than one type of voice alarm system that can be used within a building, with the code [39] providing 5 different types that can be used depending on the associated occupant activity. Once the type of system is chosen from the code [40] it has to meet the follow requirements:

Requirement	Description
1.	The voice message shall be preceded by an attention drawing tone/signal.
2.	A suitable message (either recorded or synthesized) is provided which can be automatically transmitted in response to a fire signal, either immediately or after an agreed delay.
3.	All voice messages are clear, short, and unambiguous.
4.	The level of sound in the building satisfies the required for sound levels, except that the level should be at least 10 db above other sounds likely to persist for 30s or more. The present sound pressure level shall be achieved automatically on activation of the voice alarm and shall not be alterable during the alarm condition.
5.	The received message is intelligible.
6.	Other signals cannot be confused with the fire alarm signals and that fire alarms signals have the highest priority.
7.	The message and the time interval between the messages do not exceed the maximum value and that 'fill-in' signals similar to those of conventional sounders are used wherever periods of silence might exceed the values stated in the code.
8.	During fire alarm conditions all audio input sources are automatically disconnected

	expect for the fire microphones and the speech modules which give the warning.
9.	If the fire routine requires messages to be given by a person, one or more microphones should be designated as fire microphones. These shall be permanently connected to the voice alarm system. So that announcements and instructions can be given. Access to the fire microphones should be limited to authorised persons. Only one fire microphone may be active at any given time.

Table 4: Design requirements for VA system [40]

Once the system is designed it is essential to consider the link between the fire detection system, the fire alarm system and the voice alarm system, as it is important to maintaining the usefulness of the overall system in its ability to warn the occupants and facilitate evacuation. Hence, the most important design feature of a Voice Alarm system is the emergency messages themselves. The broadcast of an emergency message needs to be immediately recognisable by the occupants who find themselves within an emergency. If the message is direct and precise it can help to convey the sense of urgency required of the occupants while providing a calming influence on the overall evacuation. The messages need to draw attention to the urgency of the situation and at the same time be intelligible. However, if the message is too long, occupants might not be able to assimilate the information provided in detail and will wait for repeats. If the message is too short, the amount of information may not be enough to facilitate evacuation. The gap between messages is also important because if it is too short occupants might not realise the message has ended and if it is too long occupants may wait for the message to repeat for clarification putting them at risk for longer. Below (see Table 5) is the recommended format for a pre-recorded emergency broadcast from start to finish. It is important to repeat the sequence until it is manually silenced by a person with authority, for example a fire steward, to ensure that every occupant within the building has heard and reacted to the evacuation message.

Attention-drawing signal	Lasting 2 s to 10 s followed by
Brief Silence	Lasting 1 s to 2 s followed by
Evacuate Message	Followed by
Silence	Lasting 2 s to 5 s

Table 5: Recommended sequence for audio message, [41]

The sequence relies on the message itself being at a high level of intelligibility in order for its use as an effective evacuation tool. The requirement for intelligibility pertains to the area of the loudspeaker itself and in other parts of the building there may be more remote occupants. Hence, they will not receive the message clearly and the required audibility and clarity required for the intelligibility of the message may not be achieved. The intelligibility and clarity of the message can be affected by how far the person is away from the loud speaker (source) due to the amount of reflection that occurs from the message bouncing off walls/obstacles within the building. BS 5839-8:2008 provides guidance on how to design the system with regards to audibility and clarity while also providing a solution on how to measure the intelligibility of a message.

If an audible message system is installed within a building, it will normally be used for tasks other than evacuation messages. Therefore, it is important that all broadcasts are ranked in order of priority so the evacuation message may override less important messages/uses (for example, background music). The code [41] provides the designer with a suggested order for the priority level of messages which are given in Table 6 below:

Priority level	Type
1	Emergency microphones.
2	Pre-recorded evacuation message regarding potentially life threatening situation needing immediate evacuation.
3	Pre-recorded alert message regarding dangerous situation nearby requiring warning of potential evacuation.

4	Other emergency pre-recorded messages.
5	Non-emergency messages.

Table 6: Priority level of messages

4.5.3 Directional audio

Directional sound technology has only been in development since the mid 90's [42]. It is intended to work with current alarms and signage to help provide additional information to occupants in order to facilitate faster response times and improve total evacuation times. Directional audio was first developed to find a solution that could help visually impaired occupants evacuate safely without relying on the help from other occupants. However, during the research of the technologies it was found that the use of directional audio had other benefits [44], which are listed below:

Benefits
Provide additional sound cues to assist occupants in locating the nearest exit rather than their instinctive urge to exit by the route they entered.
Independent of language. It is simply an auditory cue that directs occupants to an exit.
Can help occupants orientate towards an exit in a smoke filled room.
Increases reaction to alarm signals.

Table 7: Additional Benefits of directional audio [44]

Even though it has been shown to be very beneficial, directional audio is still rather undeveloped compared to other audio tools and hence it is not often used as a solution within an evacuation design. The code states [40] that the intention of the system is to help occupants identify possible escape routes and guide occupants toward their nearest escape route, which they potentially could have overlooked. It should be noted that visibility can be impaired not just by fire conditions but also by the nature of the environment and the people within the environment, hence, this is why they have been developed to be used within cruise ships.

There is a single code [43] used as the standard for the planning, designing, installation, testing and maintenance of the system, yet, it is a very basic standard compared to other examples referenced above and calls upon a publicly available specification (PAS) [44]. When this PAS is used the performance requirements and method of testing are provided that notes the key points of the systems sound patterns, durability and construction are require to meet the same standards as the basic audio alarm disused above.

The testing procedure for the sound level and frequency for the sounders is based upon the measurement produced by the sounder when it is placed in a free field or simulation free field condition. The procedure is as follows (Table 8):

1.	Mounting arrangement according to the manufactures instructions.
2.	Measure and record the A-weighted sound level in dB using the fast detector indicator characteristic.
3.	If sound is fluctuating, take the max value indicated during at least a complete cycle of the sound pattern.
4.	Take one value at a radius of 3 m from the reference point of the device for of the following microphone positions:
	Overall sound level at 30° intervals from 15o to 165° through a semi-circular arc centred at the reference point of the device.
5.	One third octave measurements shall be taken at 150, 90° and 165° centred at the reference point of the device.

Table 8: Testing producer for sound level and frequency [43]

The directional test for the sounders is a subjective test that uses a group of test subjects to determine the location of sound bursts produced from numerous possible positions [43]. If the occupants cannot determine the locality of the sound being emitted then the sounder cannot be labelled as a directional sounder.

Even with the extensive use of audio alarms within a building, evacuation designs still require the occupants to successfully navigate through a building in order to reach safety. This is often achieved with the use of visual aids such as illuminated exit signage and lighting.

4.6 Visual

Visual tools are a necessary design requirement that can be used to help facilitate evacuation movement whilst also guiding occupants through a building towards an escape route and eventually to a "safe" location. The following section will discuss the design requirements for evacuation lighting and signage whilst discussing the development and use of newer technologies known as photoluminescent material.

4.6.1 Lighting

The lighting within a building is required to be at a suitable level in order to provide occupants with the ability to move along the route to a place of safety without being hindered. Emergency lighting can be divided into four types [45]: emergency escape lighting, escape route lighting, open area lighting and high risk task area lighting (Table 9). Each type of lighting has an objective during the evacuation of a building.

Type	Objective
Emergency escape lighting	Enable safe exit from a location in the event of a failure of the normal supply.
Escape route lighting	Enable the safe exit from a location for occupants by providing appropriate visual conditions and direction finding on escape routes and to ensure that

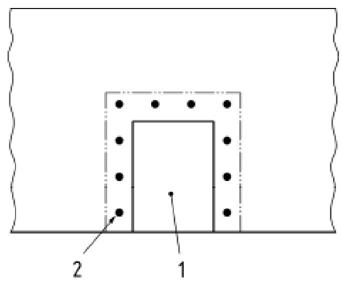
	fire fighting and safety equipment can be readily located and used.
Open area lighting	To reduce the likelihood of panic and to enable safe movement of high risk task area lighting for occupants towards escape routes by providing appropriate visual conditions and direction finding.
High risk task area lighting	To contribute to the safety of people involved in a potentially dangerous process or situations and to enable proper shut down procedures to be carried out for the safety of other occupants of the location.

Table 9: Types of emergency lighting

Lighting is required to provide luminance near each exit door and at positions where it is necessary to highlight areas of potential danger or safety equipment. The lighting is also required to accentuate the location of each exit door that is to be used during an evacuation, near stairs in order to provide light to every flight, near any change in level, mandatory emergency exits and safety signs, at each change of direction, at each intersection between corridors, near to each final exit, each first aid post and each piece of fire-fighting equipment and call point [46].

The use of flashing lights as a visual way-finding tool is only briefly mentioned within the design codes [47], however, the code only applies for pulsing or flashing visual alarm devices such as rotating beacons and does not discuss the use of flashing lights to guide occupants through a building during an evacuation.

However, use of flashing lights is mentioned briefly within a draft of the next standard [47] concerning the requirement for evacuation lighting in road tunnels. Under marking of the emergency exit it is recommended that the lights flash to attract the attention of fleeing pedestrians. The draft also provides a recommended frequency flashing range of 1 Hz to 2 Hz, with luminous intensity not lower than 150 cd in all emitting directions (taken from the Swiss design codes) and an example of how to arrange the lights (Figure 30).



Key
1 Emergency exit
2 Green emergency exit marker light

Figure 30: Example of how to arrange flashing lights around an exit [47]

Currently, research is being conducted into the use of flashing lights to attract occupants to an exit during an evacuation [31] and is producing promising results. Eventually, after enough research is conducted, the use of flashing lights as an evacuation solution could possible become an addition within the code and a requirement depending on the activity performed in the building.

4.6.2 Signage

The use of signs and signage systems are an important part of the overall fire safety strategy of a building and can help facilitate evacuation [49]. Communication is a fundamental factor of an egress situation and hence the signs need to be clearly visible and unambiguous for a speedy evacuation. This is very important in buildings where occupants may not be familiar with the layout. The required code of practice [48] for escape route signing, gives the designer the specific requirements needed when designing the signage for the escape routes within a building. It covers the location of the signs, mounting height, type of signs, lighting requirements, size, viewing distance, durability, suitability and diagrams showing how escape route signs should be used in various typical situations.

The design of the fire safety signage should consider the use of the premises, the legislation applicable to the building and the requirements, the management system controlling the use of the premises, the fire detection and warning system provided, the evacuation strategy for the premises and the degree of familiarity of the occupants with the premises. The ideal design of the escape route signing system should provide simple identification of the means of escape to allow the occupants to escape without assistance, even when under the effects of stress. The signs must provide occupants with clear and distinct directions from any point within the building throughout the escape route until they reach a place of safety.

A major requirement of the code is that all signs must be illuminated under normal conditions and signs that are internally lit or back-lit must remain illuminated in the event of a power failure, in order to provide the required information to the occupants at all times [42]. In the event of a total black-out occupants must rely on their sense of hearing and touch in order to find an exit; however, research is still being conducted into the use and improvement of a photoluminescent material that could be used in such a situation [50].

Photoluminescent material (PLM) is an inorganic chemical compound that can be used as a method of marking fire safety egress paths. PLM is also referred to as photoluminescent pigment, phosphors that are encased in flexible or rigid strata or dispersed in a liquid (e.g. paint) allowing it to be applied to exit signs, directional signage, door markings, pathway markings and other components that comprise a safety way-finding system [42].

The crystals can be characterised as being photoluminescent due to the fact that when they are exposed to a light source they have an ability to store light photons, consequently showing luminescence over time. Hence, if a power failure occurs due to a fire, the photoluminescent markings will be able to aid evacuation by guiding and directing people to safety. However, as time progresses, the energy stored within the crystals will continuously dissipate until they are completely depleted; they can be recharged again only by re-exposure to light. Currently, within the British Standards there is no mention of the use of photoluminescent materials or the design requirements for their use as an evacuation tool.

4.7 Evacuation Plan

As previously stated, the fundamental design principle of any evacuation plan is ensure that if an occupant was to find themselves within a dangerous situation, the design of the building and fire safety equipment can afford them enough time to exit the situation before being overcome by hazardous conditions. As such, they are developed to ensure the safest and most efficient evacuation can be achieved by any occupants who find themselves within an emergency. Therefore, the correct choice of fire safety systems and the development of a structured evacuation procedure to follow are highly important.

The choice of fire safety systems is dependent on the activity within the building and combines both passive and active systems. Passive systems involve using fire-resistance rated walls and floors to create smaller fire compartments which are meant to prevent or slow the spread of fire from room to room to allow occupants more time to reach an area of safety. Active systems include everything from manual or automatic fire detection (i.e. smoke or heat detectors) and fire suppression (sprinklers). It is the active systems that will be used to detect the fire and thus activate the alarms within the building to initiate the evacuation. The detector type is either prescribed within the codes, based on the activities and occupant load within the building, or through fire modelling based on the engineering judgement.

The next step of the evacuation plan is to determine the number of routes within the building needed for egress, based on the worst case calculated occupant load, and how information on these routes will be provided to the occupants during an emergency. The information is provided by audio and visual tools and the specific type of tool to use within a design is determined by specific codes, as discussed above. It is the combination of these tools that has a significant effect on the evacuation procedure and the efficiency of the evacuation plan. The tools are often determined by the activity within the building, for example, within an office building the occupants are assumed to be alert, awake and familiar with the exit layout and therefore only a sound based alarm bell, emergency lighting and exits signage is normally used to aid evacuation. However, within a shopping complex, occupants are assumed to be alert, awake yet unfamiliar with the exit layout and a voice alarm or PA system is adopted to help guide occupants and facilitate their movement.

A common feature of many evacuation plans involves the use of an "occupant of authority" to help occupants during an emergency with the goal of increasing the efficiency of the overall egress process. These "occupants of authority" are either a staff member, fire wardens or emergency service personal. The staff member and fire wardens are required to provide assistance during an evacuation by ensuring other occupants are aware of the alarm, to initiate the evacuation and to help guide occupants towards the nearest or safest means of escape. Hence, it is vital that these people are knowledgeable on the safety processes and system used within the evacuation plan, which will involve some level of training.

As discussed within Chapter 3 most occupants will not have experienced an actual real life fire emergency, yet they would have had some form of education and/or training on what to do when an alarm is activated. This training will be ingrained within a person's long-term memory in some form or another.

However, in the case of training staff and/or fire wardens, when the alarm is activated they are required to engage a different type of memory that reminds them of the evacuation protocols they have been assigned to undertake as part of the evacuation plan instead of just reacting to the alarm and evacuating the building.

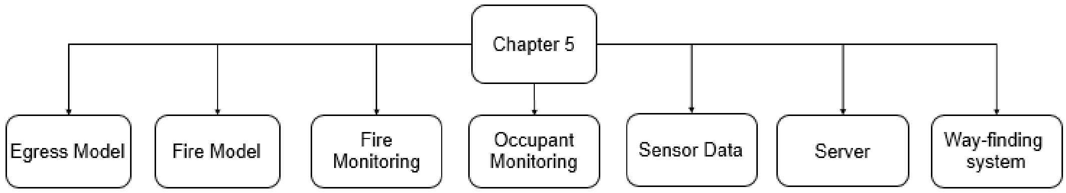
4.8 Summary

In summary, the chapter above discusses briefly the design approaches that are used as part of a fire engineering egress design and how the behaviours of occupants are simplified for design purposes, based on the chosen method. It also provides a quick insight into how evacuation plans are developed and are dependent on the requirements of design codes and the tools that are used to meet the minimum required level of safety within a building depending on the activity being undertaken. (Note: The process of using fire modelling tools as part of a design process will be discussed further within Chapter 6 of thesis).

The information gathered as part of this chapter was used to understand the design processes that are being used within consulting firms and how they are used to determine the fire engineering tools provided within a building in order to ensure that they the I.D.E.S. development can be integrated into current practice. It is these tools that will be used as part of the I.D.E.S. way-finding system, hence, it was necessary to gain knowledge on how occupants are guided to a specific egress route and the minimum design requirements needed to create an evacuation plan.

The following chapter will discuss historical attempts at information driven egress and whether the proposed system is hindered by the existing code. It will also provide a more in-depth description of the system as well as the components to be used and a graphic representation of the influence of the system on

5 Information driven egress



The basic idea behind information driven egress is that if occupants are provided with information that is influenced by the development of a fire it will allow them to evacuate the building in a safe and efficient way without confusion, given that they are more informed, thus reducing the possibility of stress and anxiety. The solution uses a combination of way-finding tools which have the ability to change the information provided to the occupant based on the information collected by the sensors throughout the building that are interfacing with a central computer server. This server will incorporate an "intelligence" process (i.e. predicting capabilities) that will also be able to alter the information provided by the way-finding tools. However, the solution will only work if the combination of the tools, sensors and systems are able to be integrated into a central control panel that can be understood and used effectively by fire service and/or security staff.

The idea behind the incorporation of the fire and occupant locations upon a graphical display within the central control panel is to provide as much information as possible to the fire service in order to improve their abilities to fight the fire and save people's lives. During the design of the panel it will be necessary to include the Fire Service as their input will be vital on determining the appropriate amount of information which should be provided and how it is displayed, in order to increase the usability of the panel. However, this will not be addressed as part of this thesis as it is considered to be part of the required future work. The task of finding an occupant within a smoke-filled room is difficult and time consuming, and it is not often known if any occupants are actually within the room being searched. By providing the fire service with information on the location of occupants compared to the location of the fire/smoke can limit the amount of time needed to safely search the building before the conditions become untenable.

The information driven evacuation system will hope to build upon the systems that are currently used as part of a fire safety design, to improve the efficiency of an emergency evacuation.

5.1 Historical attempts

There have been numerous journal articles and conference papers addressing the theoretical topic of the use of an intelligent egress solution. In May 1982, a United States Patent [52] was filed for an intelligent fire safety system, Figure 31. The system includes using smoke and heat sensors to provide information to an exit sign unit that would incorporate the use of a speech synthesizer and a strobe light to provide output information while linking the exit signs on a single floor, via a communication unit, to inter floor interfaces and a central monitoring unit. The strobe would be used to draw the attention of the occupant to the exit, with sufficient intensity to penetrate smoke in a smoke-filled hallway. The speech synthesizer would provide verbal instruction to the occupants within the building according to the emergency situation that was occurring. The intelligence of the system in this thesis is defined by its ability to use the sensors within a building to gather information on the development of the fire/smoke during an emergency and using that information to influence the predictions it creates via a steered computational model.

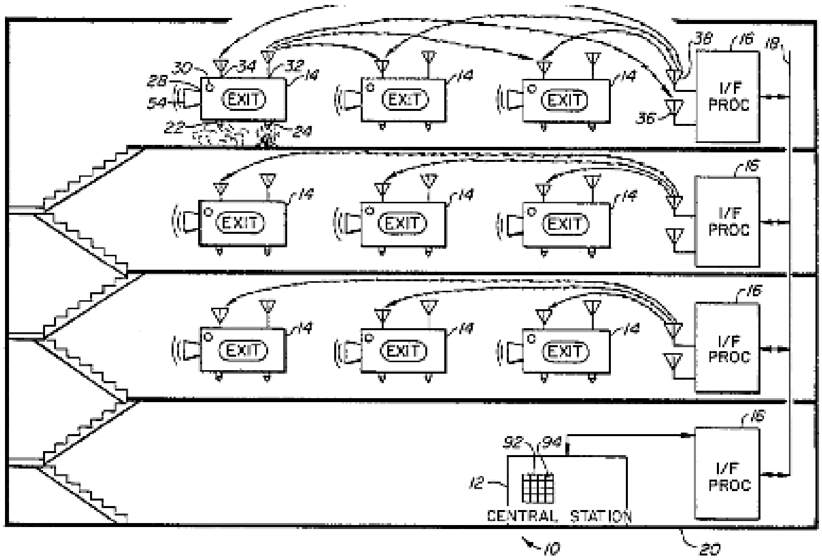


Figure 31: Proposed intelligent fire safety system within patent [52]

The patented system was developed to remove the possible breakdown and failure of the more commonly used centrally controlled systems of the time, due to there being an information overload, which has also been experienced during experiments conducted at the University of Edinburgh [51] – where detailed information must be communicated to a central station for processing before an alarm could be issued to instruct the occupants within the building. The creators stated that this lack of guidance and reliance on the central control system to issue an alarm had in the past resulted in unnecessary injury and death due to occupants misinterpreting the alarm signals. The patent was issued in July of 1985.

In 1989, Piggott [53] published a paper that combined two separate research topics, the first being human behaviour in fire and human response to information fire warning systems, and the second being computer-based automatic fire detection systems ('Intelligent fire alarms'). The paper attempted to summarise the topics, while combining the points with observation made about first aid fire-fighting within the UK to develop a new fire protection strategy. The proposed "Intelligent Fire Alarm System" was developed to try to create a solution to reduce the number of false alarms while providing occupants with information about an emergency if one was to occur. The key point of the paper was that there had been a dramatic reduction in the price of computing equipment and that new systems designs should consider implementing the use of computing technology.

As the development of computer systems continued through the 90's and the 00's, Miller-Hookes and Krauthammer published a paper in 2006 [54] that discussed the concept of an intelligent system that incorporated evacuation, rescue and recovery. The concept came into fruition due to the terrorist incidents, such as the World Trade Centre, which demonstrated that personnel responsible for decision-making in post-attack and structural fire evacuation, rescue and recovery activities would significantly benefit from an expert decision support system. The system would use sensor technology to create a real-time assessment of the extent of blast and fire damage to a building, while providing information on how to mitigate the situation and prevent further deterioration. It would also monitor the growth and spread of fire and smoke to aid rescue workers and evacuees in rescue efforts and safe egress. The system would combine a near real-time intelligent blast damage assessment/target vulnerability assessment tool and on-line emergency, rescue and recovery retailed optimization techniques. At the time of publication the system was only in the development stage and a prototype of the ERR concept has been created within a model program known as FlexSim simulation software for testing [54].

In July 2007, full-scale fire tests were conducted by the University of Edinburgh, in association with BRE Global. The tests, referred to as the Dalmarnock fire tests, were the precursor of a project known as FireGrid [51]. The goal of the FireGrid project itself [55] was to combine the use of a computational fire simulations tool with real-time information derived from sensors in a building to provide valuable information about the current fire conditions, and, via steered models, their possible evolution. The real-time data gathered via a variety of sensors was replayed and the model exercised in an attempt to predict the evolution of a fire within an apartment at the Dalmarnock tower blocks. The success or failure of this approach would determine the ability of using sensor and a Monte-Carlo based computer model as part of a sensor-linked system for efficient evacuation.

The most recent attempt, other than this thesis, at the development of an information driven evacuation system is being undertaking by Dr Christos Giachritsis and his associates. The project is known as Getaway [56] and focuses on the use of an integrated active and intelligent directional emergency signage system within modern rail and underground stations. The goal of the system is to guide occupants within the terminal towards a safe route, away from hazardous conditions, according to the development of the evacuation incident.

As part of the project an integrated active and intelligent direction emergency signage system with the goal of the system to “identify different routes as the incident develops and congestion, fire and its products, dictate alternative” [56]. It is hoped that future terminal computer models used as part of a design solution will be able to demonstrate the efficiency of the evacuation procedures based on whether the system has the signage installed or not. The system is broken down into three “layers” known as the hardware layer, the communications layer and the application layer. A visual representation of the system is provided below and shows the interactions that are to take place as part of the Getaway system.

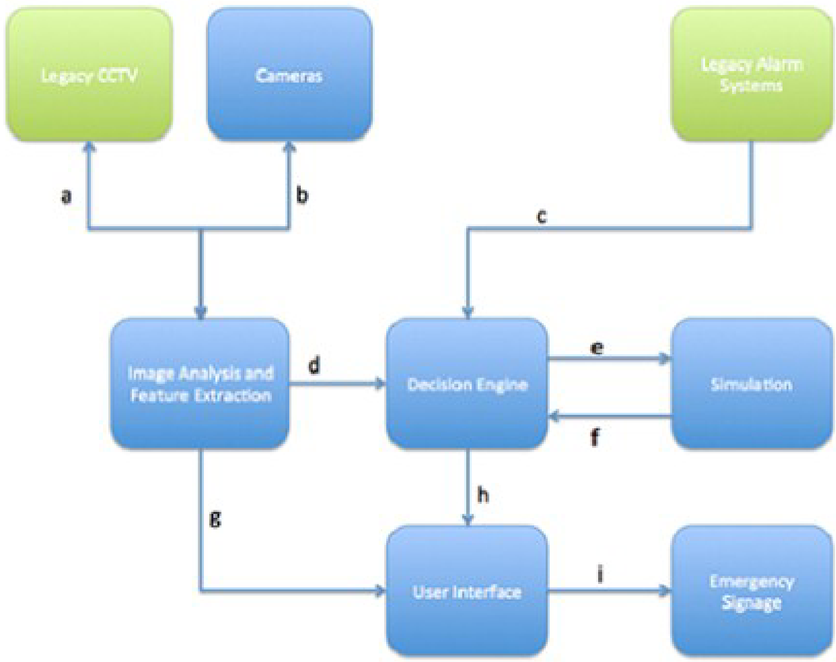


Figure 32: Process diagram of the Getaway system [56]

As stated within Chapter 2, the Information Driven Evacuation System will incorporate the use of both audio and visual way-finding tools to help guide the occupants towards an exit. It will provide live information to the occupants while reducing confusion about alarms, therefore reducing the amount of time for occupants to start their egress movement. If the system can reduce the reaction time of the occupants and direct them to a safe and close exit this would significantly increase the effectiveness of the evacuation and the fire safety design of any building.

So far the four high level components of the system have been discussed (real time sensor data, the server, the prediction model and the information driven system itself), yet, the required individual components required by the system have yet to be addressed. The following sections will address the required components needed for each of the processes that the author of the PhD deems are required and how they will be conducted by the I.D.E.S.

5.2 Sensors

5.2.1 Fire detection

This section of the sensor-linked system requires the use of sensors that are common place within any building; their installation is generally required as part of the building codes fire safety strategy. A variety of sensors are available to be used as part of a system to detect the presence of fire/smoke within a building, with the more common sensors installed accessing the change in temperature (heat detectors) or the reduction of the light density within the room (smoke detectors and beam detectors).

Heat detectors are designed to measure the changes in convected thermal energy that are caused when a fire increases the temperature of a heat sensitive element. There are two types of heat detector which are classified by the operation they conduct. Fixed temperature heat detectors are the most common type of heat detectors and operate when the heat sensitive eutectic alloy reaches a temperature when it changes state from a solid to a liquid. Rate of rise heat detectors incorporate the use of two heat-sensitive thermocouples, with one monitoring the heat transferred by convection or radiation while the other responds to ambient temperatures. The detector is activated when the contacts within the sensor are closed which may occurs for example when the temperature increases at a rate of 9ºC or more per minute within the area, however, this rate changes depending on the brand of detector used.

Smoke detectors are designed to detect smoke either by optical detection (photoelectric) or by a physical process (ionisation). Photoelectric smoke detectors use an internal light source (incandescent bulb or infrared LED), a lens to collimate the light into a beam and a photodiode sensor at an angle to the beam as a light detector. The detector is activated when the smoke scatters the light in front of the photodiode. An ionisation smoke detector uses a radioisotope in between two electrically charged plates, which ionises the air causing current to flow between the plates. The detector is activated when the smoke interrupts the flow of ions between the plates.

There are also detectors that can be used within the HVAC system to analyse air participles for the development of smoke, however, these are used infrequently due to the significant increase of the cost of the product.

To incorporate the use of these sensors within the fire detection system each sensor must be installed as its own node so that it can be assessed independently by the controlling computer program. When this individual sensor is activated, a warning is then sent to the control panel and the location of the fire is displayed. The fire detection system will also activate the necessary alarms required to provide the initial warning to the occupants about the fire within the building. Once the location of the fire is acquired the sensor-system can then access the location of available/blocked routes within the building, however, for the way-finding system to work efficiently it needs to know the location of the occupants first.

5.2.2 Occupant detection

This section of the sensor-linked system requires the use of motion sensors that are commonly used as part of a security system, either for business or residential purposes. The most common type of sensor used incorporates a passive infrared sensor that measures infrared light radiating from objects in its field of view. It is able to measure the heat energy emitted, in the form of infrared radiation, from an occupant that then signals to the security system that a person is present within the room. The term "passive" in this instance refers to the fact that the sensors do not generate or radiate energy for detection purposes and work entirely by detecting the energy given off by the occupants.

The term "motion sensor" is an incorrect labelling of how the sensors actually work as they do not detect motion per se. Instead, they are programmed to detect abrupt changes in temperature at a given point. If an occupant was to walk into the room the sensor will detect the quick change in room temperature to the occupant's body temperature and then back again. This quick change is detected by the sensor causing the alarm, noting that moving objects of identical temperature will not trigger the sensors.

As with the fire detection sensors each of the motion sensors incorporated into the system must be installed as its own node so that it can be assessed independently by the controlling computer program. The occupant detection system during normal conditions would remain inactive and would only activate once a fire had been detected within the building. The system will then display the location of the occupants upon the control centre panel. Within the initial stages of the fire the occupants will be detected using a combination of thermal motion sensors, to detect non-moving people, and security sensors, to detect moving people. The thermal motion sensors will eventually become redundant once the fire spreads throughout a room, however, the controlling computer program will continue to display that occupants are in a room until all thermally detected humans are out of the space.

Of course this type of sensor is not the only technology available that can be used to detect an occupant's movements within a building. The system could incorporate the uses of GPS, pressure pads, lasers, etc as tools for detecting occupants. However, as the cost of retrofitting/installing these technologies may be considered too expensive, it would be considered more cost effective to incorporate the use of security sensors within a building as they are commonly installed as part of a performance-based design requirement.

The data from the sensors will also in principle be able to provide information to the system on which routes have been blocked by the occupants due to a significant increase in usage. The system would incorporate this information along with the location of the fire/smoke and the occupants within the building. Therefore, the way-finding system will then be able to determine the safest and most efficient egress routes available to evacuate the building [32].

5.2.3 Egress route recognition

The final section of the sensor-linked system requires the information gathered from the fire and occupant detection sensors in order to determine the type of way-finding tool needed to be activated and the information that should be provided.

The way-finding system is the combination of both audio and visual tools that can be used to either encourage the occupants to move towards certain exits that are "safe" and available for egress, or to warn the occupants about egress routes that have become blocked by the fire/smoke and are dangerous.

In order to improve the efficiency of an evacuation, occupants need to be provided with up-to-date information that is easy to understand, in order to reduce the confusion that could occur, that will guide them to a safe place. The occupants must also feel that they can trust the system and that it will guide them to safety, or they will likely choose to ignore the information and head towards an exit that is familiar. This exit may be unavailable, dangerous or further away than the nearest safe exit [32].

The following sections will discuss the available way-finding tools that could be used within the system, while determining if they have the potential to be confusing for the occupants.

5.3 Audio/visual way-finding tools

It is proposed that the way-finding system will use a combination of audio and visual tools to provide occupants with live information to help facilitate an efficient evacuation during an emergency. The system will be able to determine whether a route is available to be used, and if not, it will have the ability to divert occupants to a safer means of escape. However, as stated above, the tool may be confusing for the occupants to understand, due to lack of training or increased levels of stress felt during an evacuation, leading to the information being ignored. The following sections will break down the plausible audio and visual tools that could be used within the system that would require little to no training to understand.

5.3.1 Audio tools

The use of simple audio tools is common within a building to engage occupants to evacuate when a fire is detected. An alarm tone is a universal symbol for an evacuation and is often a good tool to use to warn occupants of the possibility of danger. However, due to numerous alarm tests and false alarms, occupants often choose to wait till they are told by others to evacuate or, in some cases, choose to completely ignore the alarm [58]. Despite this possibility, it is proposed that alarm tones will be incorporated within the sensor-linked system to provide the initial warning to the occupants that an emergency is occurring.

In order to get the occupants to believe that the alarm tone is not a false alarm/test the proposed system will use speakers to provide a voice message that will be broadcast throughout the evacuation and will vary depending on the type of information that needs to be provided. Before the type of message can be determined the initial design decision is whether to use a live or recorded message. Occupants tend to be more open to follow a message that appears to be given by a human and not a machine [59] hence this is the preferable option.

However, as the system proposed here is to be used throughout the building and is intended to have varying information within each egress route, this is not practicable. Therefore, to try and recreate the effect of a live message they will be pre-recorded using a voice actor, with the system determining the audio message to be played and its location during the live evacuation.

As discussed within Chapter 3, the broadcast of an emergency message needs to be immediately recognisable by the occupants while being intelligible during an emergency. If the message broadcast does not draw attention to the urgency of the situation it may be able to provide the information to the occupants before they choose to ignore it. For this reason, it is proposed that directional speakers will be implemented in order to increase the effectiveness of the audio messages in guiding occupants towards an exit.

As discussed by Withington [60], behavioural studies have repeatedly shown that occupants are more than likely to use their natural instincts during an evacuation and choose to leave by the same route used for entry, as it is familiar. However, these exits are often neither the quickest nor the most appropriate. The use of directional audio speakers can increase the likelihood that an occupant will discover an unfamiliar and closer exit.

The speakers used within the sensor-linked system must meet the building code requirements, as discussed in Chapter 4 and work by creating an area of sound that can only be heard once an occupant has moved into its audio zone. The message provided by the speaker will only be heard by the occupants as they walk near the audio zone and are required to be set to a decibel level higher than that of the alarm tone. This reduces the effects of audio contamination that could occur between nearby speakers that are playing alternative messages about the emergency.

5.3.2 Visual tools

The use of egress signage is a necessary design requirement of the building code and is the most basic form of tool that can be used to facilitate directional movement through a building towards an escape route and/or an exit. Exit signs are very common within any building and are easily understood. However, as demonstrated during the station nightclub fire [61], conflicting exits sign can lead occupants to often misinterpret, miss or ignore exit signs causing them to head towards an exit that is of familiarity as they feel they know it will lead them outside the building, which during an emergency is the most desirable location. Standard exit signs are able to help direct occupants towards an exit, yet, do not have the ability to warn occupants that the exit may be unavailable. Variants of the standard exits signs are currently being installed within buildings in Auckland, New Zealand that try to address this issue (Auckland Council et al 2011).

The first variant involves the installation of a green sign next to a red no exit sign with activation depending on the situation within the egress route, as seen in Figure 33.

Figure 33: Exit signage variant 1

If the route is clear the green sign will activated, and vice versa; however, these signs can be confusing due to fact that during the daylight hours it can be nearly impossible to determine which sign is activated. The signs, as they are currently designed, could be potentially confusing, thus they will not be used within this system.

The second variant involves the installation of a standard exit sign with a new sign that when activated is illuminated red and states " Fire Alarm Do Not Enter" with an additional plaque with "If Do Not Enter sign is illuminated exit via….." as shown in Figure 34:

Figure 34: Exit signage variant 2

These signs are adopted to direct occupants away from everyday routes (commonly used) that are considered to be inadequate to be used during an emergency evacuation. The sign provides occupants with an overload of information to process during an evacuation which can become confusing and therefore will not be used within the proposed system.

Certain colours are ingrained into our memories [62] to a point where it is universally recognised that green means safety and red means danger. Therefore, the use of these colours can be incorporated into a possible way-finding solution that would require little to no training to be understood. The use of LEDs are a possible simple solution that can be employed as an extra visual stimulus to provide information to the occupants. As discussed, the colour green is commonly used upon standard exit signs, and is a great way to attract occupants towards a means of escape. However, when the route becomes unavailable the green exit sign still remain lit. Therefore, the simplest solution would involve using a standard exit sign that can be turned off and blocked if the exit route has become unavailable or create a sign, using LED lights, which can flick between a green exit sign and a red no exit sign at a moment's notice. It should be noted that there are exit signs in other countries that do not use the colour green, for example, red is used instead in Japan. However, the colour green within these countries is still utilised for cross walks and traffic light to mean "Go" or "Advance", hence, it is still associated with a positive travel direction.

Furthermore, LEDs could be placed around the frame of a door on an egress route and depending whether the route is blocked or not show a different colour, i.e. green for clear and red for blocked. Research has been conducted [63] into the use of providing constant green strips along an egress route in order to encourage and reassure the occupants that they, even within a smoke-filled corridor, are heading towards a safe exit way. However, the amount of LEDs used within the corridor creates an unappealing visual situation during its normal usage, hence, photoluminescent materials have been suggested as an alternative solution [63].

The photoluminescent material can be used to create fire safety markings that will be able to be used by the occupants during an emergency if the lighting fails. The most promising application of the product is the creation of safe path markings with potential to guide occupants to an exit in total darkness, see Figure 35.

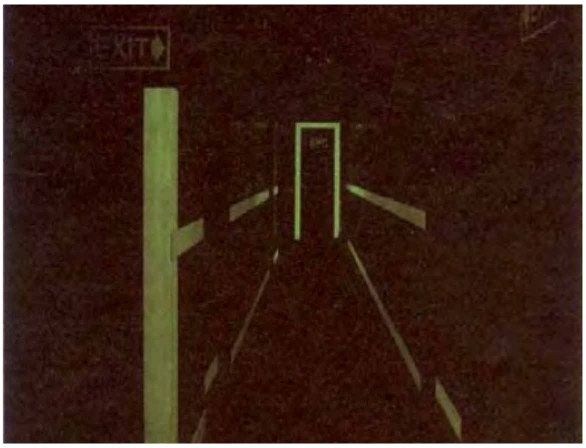


Figure 35: Safe path markings in darkness

Even though results from evacuation trials have shown the product to be very effective at guiding occupants towards an exit during a blackout [63] it cannot be utilised within the sensor-linked system. This is because the material itself cannot be controlled via a computer program, as it is a passive solution that can display one colour at a time and requires to be charged via a light source, meaning it can lose its charge and fail during an evacuation.

5.3.3 Summary of tools to be used

The way-finding system used within the sensor-linked system will need to incorporate the use of audio and visual tools in order to provide occupants with live information about an emergency that is accurate and easy to understand.

It is proposed that the audio tools used within the system will be directional audio speakers above egress doors that will either play a message encouraging occupants to use the exit or a message that warns the occupants that the route is blocked/unavailable due to the development of fire, smoke or over use.

The visual tools used within the system will be standard exit signs, which will have the ability to be turned off if the route is unavailable, and LED lights around the frame of the doors that are used as part of the available egress routes, which will either display a green or red colour depending on the route's availability.

It is believed that the combination of these tools will be able to provide the occupants with the information required to evacuate the building in a safe and efficient way without causing confusion, thus reducing the possibility of stress and anxiety. However, the solution will only work if the combination of the tools, sensors and systems are able to be integrated into a central control panel that can be understood and used effectively by fire service and/or security staff.

5.4 Visual representation of the system influence on evacuee performance.

The following figure is a visual representation of how the system would in an ideal situation influence the evacuation efficiency and improve an evacuee's performance.

As the system is constantly monitoring the conditions within a building via the sensor installed, and through the central sever, it is assumed that the detection time of a fire will be reduced compared to normal automatic alarms. This is also the reason the alarm time is reduced for any situation once the system is installed.

The major goal of the system is to reduce the time taken for the occupants within the building to react to the alarm, reduce their pre-movement behaviours and reduce their travel time due to efficient egress route selection. Hence in an ideal situation the occupant will notice the alarm, the lights and the audio messages that will be activated by the system on detection of the fire much quicker than just a normal building wide alarm made by traditional sounders.

The activation of the system will lead to a very significant atmospheric change in the building compared to the normal everyday conditions. This should reduce the response time of the occupants due to human inquisitive behaviours [18], meaning at least some of the occupants will investigate the new information provided by the system. It is assumed that the “leader” type occupants within the building will assimilate the information provided by the system reducing the confusion over the alarm and through the process of data sharing the information will be passed from the “leader” to the “led”. This will reduce the response time of the occupants within the building.

Finally, as the system is provided with way-findings that can be changed to display different information depending on the data gathered from the sensors and predicted by the modelling tool, it will have the ability to determine the most efficient egress routes from the building. Therefore, if the tools are successful at guiding occupants down the best routes determined by the system it will decrease the overall travel time as it is hoped that the system will deter occupants from the familiar, and often longer, routes within the building.

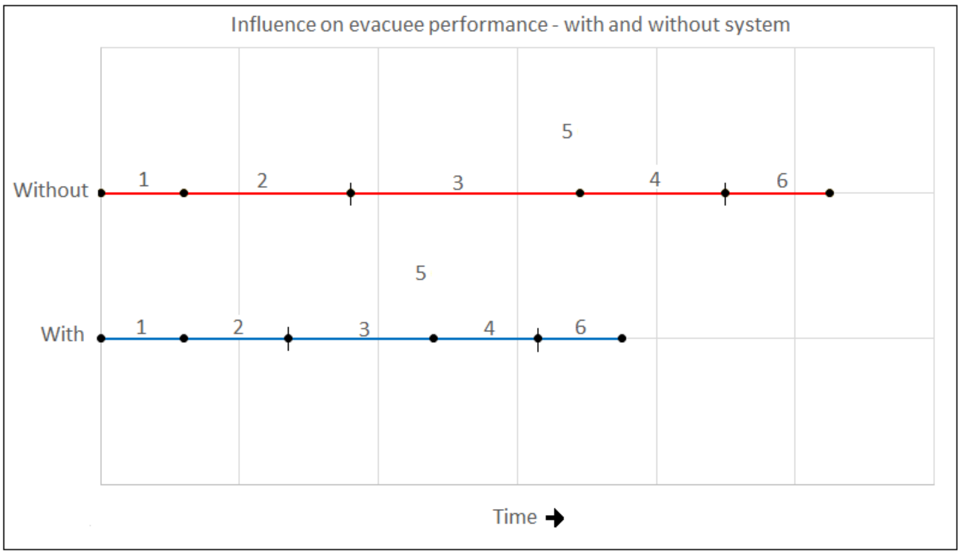


Figure 36: Influence on evacuee performance with and without I.D.E.S.

Number	Process
1	Detection Time
2	Alarm Time
3	Recognition Time
4	Response Time
5	Pre-movement Time
6	Travel Time

Table 10: RSET breakdown [13]

5.5 Strengths / limitation of System

Figure 36 gives an example of how the system would work in an ideal scenario and in the real world it may not produces a similar reduction in the required safe evacuation time as predicted. There are certainly strengths of the system that will help influence the evacuation of the occupants for the better, compared to a scenario where the system is not installed.

The first strength of the system is that the fundamental process of the system operates constantly, monitoring the conditions within a building and making comparisons to the normal condition. The system will be programmed so that the activation of two sensors/detectors or the activation of a sensors and a manual call point will be needed to sound a building wide alarm with the aim of reducing false alarms. Occupants are less likely to react to an alarm when there have been cases of false alarms within the building [18]. This process will significantly reduce the potential for false alarms within a building compared with the normal process of the activation of a single detector.

The second strength of the system is the addition of way-finding tools and its ability to manipulate each tool to provide information to the occupants. Providing occupants with information about the changing conditions during an evacuation will help facilitate the evacuation and increase the efficiency of the process as it will reduce the confusion felt due to the unannounced alarm. It will also be able to determine the most appropriate route for the occupants to take to evacuate the building in the quickest and safest manner.

The final strength of the system will be its ability to predict the movement of the fire and the movement of the occupants based on the conditions within the building. This is vital information to both the rescue services and the occupants within the building. For the rescue teams it will give them a better understanding of where the fire is located on arrival so they can focus their efforts on fighting the fire at the correct location and it will also provide them with possible locations to send crew to help evacuate trapped occupants.

This assumes that there will be no limitations of the technology to make the prediction using sensor data for both the movements of the fire and the occupants. It also assumes that the sensors within the building will be able to accurately provide information on the development of the fire or the location of the occupants. There is sensor equipment readily available that does have this ability and the process of using the information to predict fire growth will be discussed further in Chapter 6.

It should also be noted that the use of the system assumes that there will always be a continuous power supply readily available. Hence, in order to confront the possibility of a power failure either before or during an emergency the system will also have to be run on a back-up generator or be powered via an independent supply, off the site of the building or installation.

The limitation associated with the monitoring procedure of the I.D.E.S. is that it relies on the information on the normal conditions to be calibrated correctly and does not allow for a change in these conditions. It also assumes that the fire growth will either be sufficient enough to activate two detectors or that an occupant will be alerted to the fire and activate the manual alarm system if not. These are minor limitation and may be address by having a test of the system once it has been calibrated using a (simulated) fire test within the building or providing ambient temperature sensors that are constantly providing measurements to the system as part of the calibration process of the I.D.E.S.

The limitation with the use of the way-finding tools within the building is due to both technological and human based factors. The ability of the sensors in the system to relay the necessary information to the prediction system, as well as the system's ability to make the prediction itself is a technological issue. If the prediction tool is incorrect with its prediction or if the information from the sensors cannot be used by the system or displayed using the way-finding tools, it may inadvertently lead the occupants away from the best route or worse towards a dangerous situation. Of course the main limitation is the occupants and if they even choose to follow the information provided by the system or whether they choose to ignore it completely.

5.6 Contributory Work

So far throughout this thesis the development and potential of the information driven evacuation system has been discussed, yet, the contributory work that the author aims to deliver is yet to be stated. The system relies on the use of a prediction model to determine the occupants' behaviour and movement during an evacuation and how this prediction is used to shape the information provided by the way-finding tools. It has also assumed that any occupant will fully understand the information provided by the way-finding tools during an emergency evacuation. However, it is unknown how the occupant's behaviours and understanding of the tool will affect how they behave/react and if they even will be able to be influenced by the tools in the first place.

This thesis focuses on the behavioural of the occupants and the development of the prediction modelling to be used within the system using three evacuation experiments to investigate occupant interaction with the way-finding tool and with each other. It will also aim to develop behavioural sets to be used within the prediction models to try and predict how the occupants would react to the system to see if the idea of information driven evacuation is even a viable solution to increase the efficiency of an evacuation.

Two of the three experiments discussed in this thesis were undertaken as part of a partnership between the University of Edinburgh and the University of Lund. Both Universities helped plan and execute the experiments, each PhD student using the same information provided by the experiments as part of their own work, yet, each would conduct their own analysis to gather the information they specifically required.

The third experiment was conducted at the University of Edinburgh and it used a combination of the way-finding tools in two different scenarios to see if (1) they were noticed by the occupants and (2) if they absorbed and used the information to help them evacuate the building more efficiently.

The behavioural sets developed from the information provided by the experiments will be used as part of a feasibility study that will demonstrate how different fire scenarios within an office building will influence the information provided by the system and how the occupants would interact with the information. The study would also compare the flow rates and overall evacuation time as well as the behaviour of the occupants for each scenario including a base scenario where the system will not be used within the model created for the study.

5.7 Summary

In summary, the chapter above briefly discusses the previous historical attempts that were made concerning intelligent egress/ information driven systems as well as one system that is currently in development, known as Getaway [56]. The types of readily available sensors that could be used for the process of fire/occupant detection and egress route recognition were detailed along with the types of audio and visual tools that could be used as part of the system.

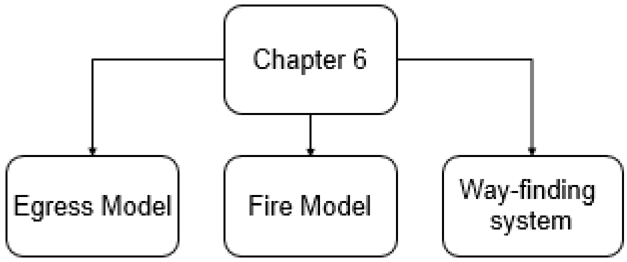
To illustrate how the ideal system with a perfect response would influence an evacuee's performance during an emergency, a visual representation and break down of the required safe evacuation time (RSET) for the system was detailed and compared to a scenario where the I.D.E.S. was not in use.

The strengths and limitations of the system were also touched upon within the chapter, with the strengths including better and earlier detection of a fire, reduction in false alarms, the addition of way-finding and the ability to manipulate each tool based on sensor data gathered and the prediction of the movement of fire and occupants within the building. While the limitations of the system were the correct calibration of the "background" normal conditions and the inability of those to be changed, the activation of two detectors needs to occur, if the system will be able to accurately predict the fire based on the information from the sensors and use it to its full potential, the ability and desire of the occupant to follow/understand the information provided by the system, and the requirement for a constant power supply.

Finally, the contributory work that the author will add to the development of the information driven evacuation system was detailed. The work will focus on the behavioural and predictive modelling side of the occupants and the interaction between the occupants and the way-finding tool with the goal of developing a new set of behavioural features that will be incorporated into the prediction models. This will involve conducting three independent evacuation experiments using the information analysed to form a platform for conducting a feasibility study that will compare the flow rate, overall evacuation time and behaviour of a large group of occupants over a series of emergency scenarios within a high rise building.

The following chapter will focus on predictive modelling including the type of models used previously, their limitations and the requirements of the chosen program for the system. It will also provide information on the selection process of the model that was used and why it was chosen.

6 Predictive Modelling



Since the late 1970s computer models have been used for predicting human behaviour during evacuation [24]. The purposes of the models are to forecast occupants' behavioural patterns and movements during an evacuation scenario. Behavioural models represent the pre-movement behaviours using a series of character defining sets of behavioural processes. Some of the processes include seeking information/investigation, warning others, setting of the alarms, etc. Movement models aim to quantify the movement and behaviour of the occupants during egress.

A majority of models, as discussed further in Section 6.6, have the ability to calculate flow rates, travel distances, evacuation times, flow paths, risk to the occupants, and location of bottle necks/queues. However, the calculations produced by these models depend upon input data created by the user, i.e. number of occupants, initial average walking speed and standard deviation. Starting location and behavioural sets are some examples of the input data required to generate a modelling simulation.

The use of modelling tools has become a standard practice and, due to the ease of availability these tools, are now used both as a professional aid and as research tools. How the programs are used by an operator is dependent on the desired purpose of the model.

6.1 Purpose of evacuation models

There is no single overall purpose of an evacuation model, as the intent of an individual model depends on the result required and who the model is for. For example a researcher may create a model to analyse the effects of removing an emergency exit from a building whereas a professional engineer may use the model to give the client a 3D perspective of the building. The following are some of the various uses for a model and their purposes.

6.1.1 Building design

Within the fire engineering design process more often than not a prescriptive code approach is used. This means that evacuation models are not often required as the building is designed by following the requirements set by local building codes [24]. However, there are cases where engineers must find a solution to a design that is not within the building code.

As mentioned previously, performance-based design is used by an engineer to determine whether or not a design can provide enough protection to allow occupants to escape before incapacitation occurs. It involves creating a model of the building and simulating several different evacuation and fire development scenarios to determine the level of safety the design can provide to the occupants in the building during an emergency evacuation. If the level of safety is satisfactory then, in theory, the occupants will have sufficient time to evacuate from the building before they would be overcome by the effects of hazardous conditions (for example, smoke). Often if a building is near the completion of a final design, a model may be used to assess the effects of a design change; for example, adding/removing a stairwell.

The most common reason a model is created within the design phase of a project is so that the engineer can have a visual representation of design to show to the clients to gain the approval to begin construction. Showing a 3D visual of a project is much easier for clients to understand than a series of 2D drawing and plans.

6.1.2 Recreating a fire/emergency situation

As with most engineering disciplines, fire engineers are able to gather and learn a significant amount of information from previous incidents. Large fires, even though they can lead to a tragic loss of life, do provide insight into expected fire development and evacuee response. For example, the use of elevators during egress is being researched [64] as a result of the World Trade Centre fires. The development of a computer model, based upon a real life scenario, can be a useful tool when trying to understand how the fire affected the behaviour of the occupants and their choices and hopefully limit the occurrence or reduce the impact of future incidents. Before a model for a design can be developed the engineer would normally require the following information (or as much as possible).

Building geometry
Number of Occupants
Location of Occupants (if possible their starting location)
Smoke movement
Items within building (for fire growth)
Location of queuing/bottle necks

Table 11: Required information need to create a model

The model will give a visual representation of the events of the fire. It can help the engineer determine whether or not the deaths/injuries that occurred during the fire are the fault of poorly designed egress paths within the building, a failure to follow the emergency evacuation plan, a failure of the alarm system or just general human behavioural issues/reasons. The main conclusion produced from the model is whether or not the occupants had sufficient time to escape before becoming overcome by the hazardous conditions, such as toxic products from smoke.

6.1.3 Research and development

Another advantage of modelling a real life fire scenario, it is allowed for researchers to gain more knowledge and understanding about the thought process of the occupants and how this information can be used to increases the usefulness of egress tools/solutions. For example, a real life fire scenario can be used for researching and developing new egress solutions (such as the effects of widening stairwells) to see whether the occupants could have escaped the situation with fewer injuries or deaths.

The majority of models that are used in research are benchmarked using experimental data from live evacuations (for example, project METRO [5]), which were conducted in order to study a new egress solution/method, to develop a new egress model or test the accuracy of a current model. In some cases this process of research and development can lead to the creation of a new egress solution or evacuation procedure that may become a standard solution in future. The “validation” of computer models using experimental data and real fire scenarios has been a common practice throughout the history of using models.

6.2 The development of computer models

The constant development and improvement of computer technology has given researchers significantly more powerful tools to generate new computer evacuation models. The basis of information used to construct these models comes from the combination of live evacuation experiments, experience from real life scenarios, human behaviour research and the development of new mathematical models and computational tools / algorithms. Another driving force behind the development of new and approved modelling tools comes from the fact that human behaviour is forever adapting and changing and therefore the models need to reflect with the new data provided.

Before the development of computer models, evacuation characteristics of a building were determined by calculating suitable escape route geometries based upon design codes/regulations and occupancy/flow rate tables. There have been researchers such as Predtechenskii and Milinskii [65] who developed more complex calculations based on evacuation trials that were considered extremely time consuming. This approach of using mathematical functions to represent the movement of occupants during egress is considered a standard approach when developing modelling tools.

6.2.1 Network – node analysis

The first computer models were based upon the 'network-node' analysis, which used the basic principle of representing a path or route as a series of nodes which occupants may move between to get from one point to another in the network. This technique was useful in determining how to reduce the time or travel distance from point to point and therefore could be applied to solve complex geometrical evacuation problems [66], [67].

The diagram in Figure 37 is a simple example of the 'network – node' approach in a one storey building where the source node is connected to the sink node by a connection known as either an arc or a link.

The movement through the network is along the arcs in the direction of the arrow. The modeller can assign characteristics to each node and arc that will determine the number of people, the travel time for each arc and the minimum flow rate of each arc. This means the modeller can use the network to greatly simplify the movement during an evacuation to obtain a mathematical system which is easily solved. However, in order to demonstration the movement of occupant in a simplified form the models sacrifice numerous evacuee behaviours as part of the process to simplify the calculations required to be made.

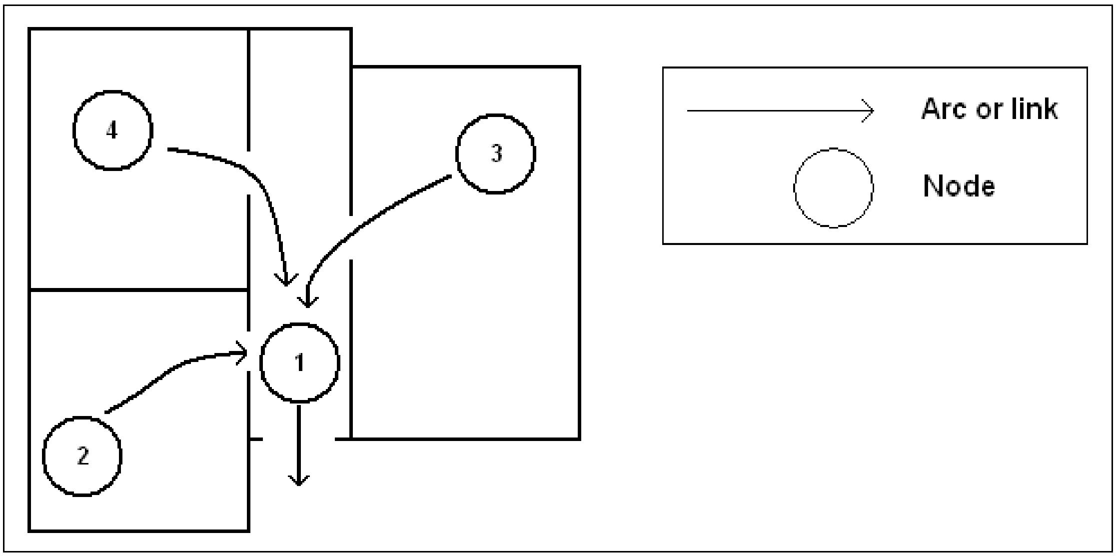


Figure 37: One Story Building Network – Node Example

The reliability of the model can be increased by dividing a room into separate areas and assigning nodes to each. This will cause the people to move along several arcs to get to the doorway node and arc to exit the room, instead of moving from a single node straight to the exit. This is because the rate of movement of the people in the model is dictated by the flow rates specified by each pathway arc, and the length of time it takes to traverse the arc. Therefore, more nodes and arcs means that the occupant can move in a more refined manner.

The main issue with the ‘network – node’ analysis is that as the geometries of the building increase in complexity the ability to model this is significantly reduced, given the simplifications made; hence, they are restricted to representing simple geometric layouts. It also suffers from an inability to model complex evacuee behaviour or incident scenarios, lacking the means to model physical interaction between occupants and how the geometry of the building can cause egress issues (for example, the effects of bottle-necking at an exit).

6.2.2 Nodal step method

The nodal step method is an evolution of the network – node analysis where instead of using a node for each room the space is divided into a mesh of linked nodes in order to increase accuracy. Each node in the room is assigned a maximum number of occupants and a distance to the exit. Occupants move closer to an exit through the grid of nodes; however, movement from one node to the next is often limited to steps at right angles, as seen in early version of models such as Evacnet or Pathfinder.

Hence, as can be seen from Figure 38, the travel distance is significantly longer travelling at right angles than if the direction of travel to the exit is at the correct angle. To alter the effects on travel distance it is recommended by some evacuation modellers [67] that a hexagonal type of spatial representation and routing finding be used, reducing the distance to the exit, thus increasing the model’s accuracy.

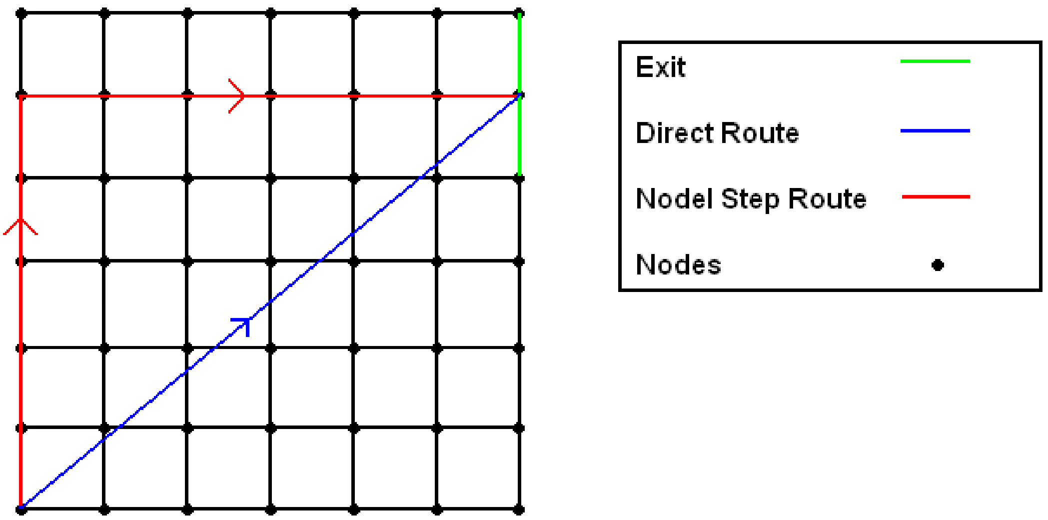


Figure 38: Nodal Step Movement Patterns

The main problem with the nodal step method is the same as the network - nodal analysis. The movement of the occupants is still restricted to a specific path; hence it cannot accurately recreate an occupant's accrual directional choice or distance travelled. Also it is unable to model the low-level physical interactions between occupants.

6.2.3 Cellular Automata Models

The cellular automata model method [68] use a dynamic system that divides the room into a regular grid of cells (Figure 39) and assigns each cell with a certain value at each time step that is influenced by the assigned value of the adjacent cells. The modeller can define a series of rules that determines the value of the cell at the beginning of each scenario. However, as it is a dynamic system, the current value of each cell is updated based upon the information produced by the surrounding cells at the previous time step. This approach means the model is able to be applied to crowd movements during an evacuation and not just the movement of a singular occupant as with the network-node approach.

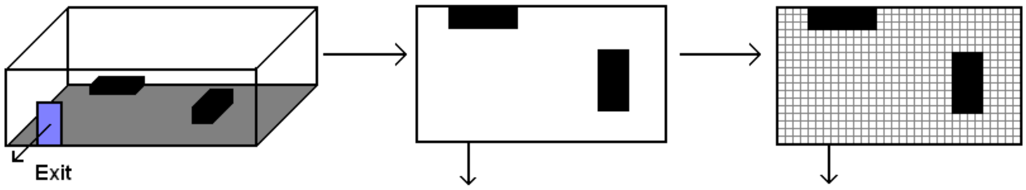


Figure 39: Cellular Automata Example

There have been two approaches using cellular automata models for the modelling of crowd movement. The first used a two-dimensional cellular automata random model to study exit dynamics of occupant evacuation. It allowed research to investigate how occupants interacted with obstacles in their way and the flow path of an occupant under various exit conditions. It also allowed researchers to simulate occupant dynamics during an evacuation and show how occupants reacted with each other. This made it possible to study the effect of queuing and crowd densities at exits. However, this approach is unusable for complex scenarios due to the fact that the crowd interaction behaviour are deemed very complicated, hence, it this approach only allows for models with one aspect of human behaviour during egress.

6.2.4 Agent-based models

The three types of models above focus mainly on the movement of occupants from one room to another; however, this mathematical approach made it difficult to model human interactions with each other and the building, leading to the development of agent-based models. These models still use dynamic systems to create a grid pattern for movement but also incorporate some sort of social structure, i.e. autonomy and interaction but not true behaviours such as relationship etc., to study crowd dynamics during an evacuation [69].

In order to simulate the interaction between the occupants the model requires each occupant to be autonomous and control their own set of unique behaviours to follow, for example, activating the alarm when a fire is detected. Using these behavioural sets to simulate each individual occupant the model can test different scenarios to see how the occupants react. This type of model can involve a large number of simultaneous calculations to be performed and therefore more computationally expensive than the models described earlier.

Further development of the social structure used in an agent-based model led to the production of models which could simulate a crowd and determine how they would react to a variety of scenarios. Hence, researchers were now able to model a crowd to investigate how they would evacuate from a building under normal conditions (no fire and calm occupants) or during a large fire (stressed occupants).

Agent-based models now include the possibility to further define the occupants with the inclusion of gender, speed, familiarity with the building, group affiliation, etc. However, even though models are becoming more sophisticated at predicting occupant movement and behaviour there are still limitations within the current generation of modelling tools, as discussed below.

6.3 Limitations

The process of modelling an evacuation is a detailed and complex undertaking. Even though computers are becoming more powerful, allowing them to support more useful modelling tools, there are still some serious limitations. The two largest limitations are the difficulty of determining the data needed to create the models and deficiencies in the representations of human responses/ behaviours. [70][71]

The majority of modelling tools are designed based on information gathered from evacuation drills and everyday movement observations. Engineers have used this data to create the empirical correlations formula and algorithms adopted to describe the movement of occupants for the models. However, the information gathered does not usually factor in the stress that occupants feel during an emergency and how it affects their movements. Unfortunately, gathering accurate movement data from live fire scenarios is difficult as it requires the occupants to recall their decisions and movement precisely during a confusing situation. Also, the information provided by the occupants may become less detailed the longer the time gap between the event and the post-fire interviews.

Even though information about occupant pre-movement times can possibly be gathered from post emergency scenario interviews it is more common for model designers to use information gathered from evacuation drills. This does create a potential problem with accuracy of the results as evacuation drills do not have the same stimuli that an occupant would see/feel during a real fire (smoke, heat, etc). These stimuli can affect an occupant emergency response time, making it unclear how much difference there will be in drill and emergency response times.

Evacuation models that include behavioural capabilities are often constrained by a lack of understanding on how humans actually behave and make decisions under stress during fires. It is unclear in many current data sets being used by engineers as to how the decision process is affected due to smoke, heat or how the occupants perceive the emergency. Current models use a measure of the level of carbon monoxide within room, known as FED (Fractional Effective Dose), to simulate the effects/conditions of a fire. These models calculate the fraction of the carbon monoxide's FED present that is affecting the occupant. The fraction correlates to a certain level of incapacitation or even death.

As discussed above, evacuation models use mathematical algorithms to estimate an occupant's response, behaviour and movement during an emergency. However, the approach of using highly sophisticated tools to model a complex process via a simplistic mathematical equation is a huge limitation. The algorithms are very useful for movement calculations, but, are very limited in how they model the response and behaviour of occupant to evacuation cues, given the lack of underlying data.

The surrounding environment and factors affecting the occupants will determine how they react during an egress situation. However these factors [72] are not often represented properly by evacuation tools. The first factor misrepresented is how an occupant perceives the fire. If the occupant does not perceive themselves to be at any risk they are less likely to react to the sound of an alarm, leading to an extended period of waiting before reaction and evacuating. The current data, based on evacuation trials, do not have sufficient information on this behaviour as it is hard to replicate the scenario for an occupant.

The location of the occupant relative to the fire can also affect how the occupant responds. The closer the occupant is to the fire the more quickly they will respond. This is due to the fact that the occupant is more likely to perceive that they are at a higher risk the closer they are to the fire. Hence, occupants will react to the stimuli with greater urgency and will leave the building sooner.

Models are able to simulate individual occupants coming together to form a group during an evacuation. However, the behaviour that occurs once a group is formed is difficult to simulate. Some of the reasons occupants form groups is so they can converse with others in the same situation and discuss the dangers and strategies for evacuating the building [73]. This discussion process within models is represented by a time delay and is determined by the programmer. However, in the real world this process allows for the transfer of information about the fire (location), the conditions within the building (smoke, heat) and movement (where to evacuate). Hence, the presence of other occupants plays a crucial role in influencing an individual's activities, sometimes for the better. There are occupants who will wait until they see others around them evacuating before they begin their own evacuation [74].

When modelling an evacuation scenario it is hard to determine what role in the building each occupant will have. The role of an occupant will change their discussion process and how they respond to an emergency. If an occupant is a trained fire warden they will tend to react quicker to an alarm and will spend time warning others to evacuate before evacuating themselves. Whereas, if the occupant is a visitor to the building, they will tend to wait for information from a member of authority (i.e. a staff member) before evacuating. The visitors will also tend to head towards the exit they entered through as they feel it will lead them directly to the outside and safety.

The ability to model an occupant's role involves the programmer creating individual behaviour sets that will alter the representations of time delays and thought processes. Current tools cannot generally update an occupant's behaviour without an input from the user. Hence, a program cannot simulate how the thought process will change, based on the cues.

The choice of exit in most models is determined by how many squares within the grid it will take to get to each exit (i.e. a distance calculation). Normally, the closest exit is chosen first by the simulated occupant. However, exit choice in a real live evacuation is based upon a more in-depth process which involves how familiar the occupant is with the building and if they have had previous experience in other emergencies. Unfortunately, the data set used to model these factors often lacks crucial information and is difficult to represent within a simulation.

It is important to understand that limitations exist within modelling tools and how those limitations could possibly affect the overall results. Each year more and more research is conducted into human behaviour, which in turn, leads to more researchers creating updated evacuation models. Eventually these limitations may be removed from the models all together. However, until that day it is important for a developer to understand the factors that affect egress modelling results.

6.4 Factors affecting egress modelling results

Engineers spend years learning and training in order to become experts within their chosen field. Before designing and constructing a building, a civil engineer normally will build up hours of work experience and knowledge. Even after the building is designed it must go through a peer review by another qualified engineer. However, with evacuation modelling, an engineer is not required to have any specialised training before using the tool to create the model. If a person desires to create a model they can purchase or download a free program and start modelling. Therefore, perhaps the biggest factor that affects egress modelling results is the person sitting behind the computer screen and their ability to use/understand the model itself.

The following are sections of a model that rely heavily on a user's input to produce results [70]:

Geometry of the building
Training/Knowledge of the occupants
Environmental factors within the building
Behaviour of the occupants

Table 12: Programmer's input into a model

The current generation of modelling tools combine all four of the above factors to model an evacuation. The level of involvement with which each of these factors are represented within the program varies in complexity from one model to the next. Hence, the user should know how each of the factors could affect the model and the results produced. The following sections will discuss how the factors could affect the models/results and what the developer needs to understand about each of them before running a simulation.

6.4.1 Geometry of the building

This is the section of the model where the user creates the environment that the occupants will be placed in for the evacuation. The design of the building is often dictated by the requirements of codes and standards (for example, number of exits, maximum travel distances, widths of corridors/exits, etc.) or by an architect's unique and ingenious ideas. However, models more commonly adopted as part of the performance based design approach are more complex due to the design being irregular and therefore geometry errors are possible.

A possible error made by the programmer is assuming that the occupants will use all exits provided within the building. Codes and standards will provide the programmer with the basic requirements for an evacuation from an emergency, e.g. number of exits required. Therefore, the programmer will tend to create a model with for example two main exits and two emergency exits (See figure 40). It might then be assumed in the model that all occupants will evacuate to the nearest exit, resulting in an efficient evacuation time. However, in reality, occupants will tend to head towards the exit that they used to enter the space, often meaning emergency exits are not used [75]. This may lead to a much longer total evacuation time and in the case of a real fire the occupants would be exposed to hazardous conditions for an increased time. Also if all the occupants tend to head towards the main exits, the corridor and exit width may not be wide enough to compensate for the extra occupants, leading to a reduction in flow rate and an increase in evacuation time due to queuing. A competent user might create a scenario in the model where all emergency exits are “blocked” to see how this affects the evacuation results.

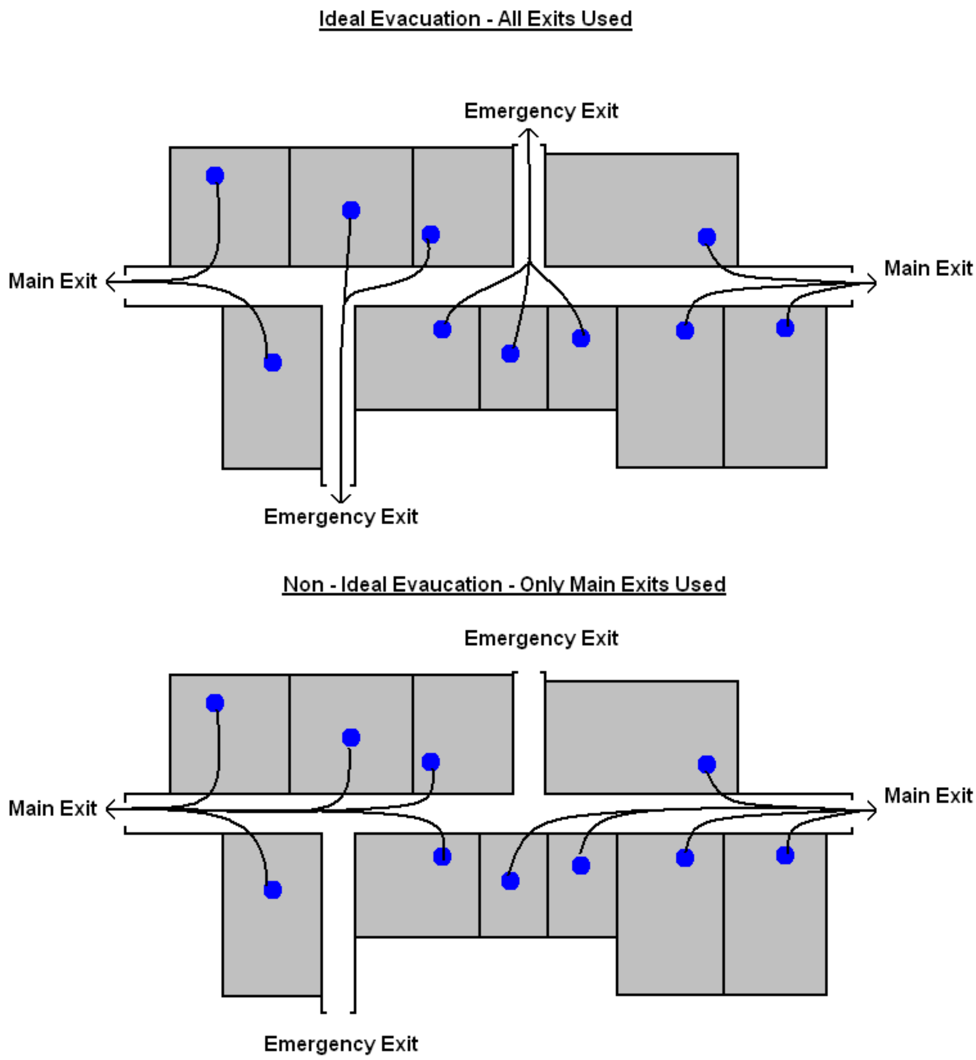


Figure 40: Ideal vs. Non-ideal evacuations

Another reason occupants may not use the emergency exits in practice could be due to confusing layout of a building. If the geometry of the building is atypical it could cause occupants to become disorientated/confused while trying to evacuate, particularly in cases where the visibility is reduced due to the smoke (i.e. a real evacuation). This may lead to the occupants missing an emergency exit and reverting back to the entrance/exit which they used to enter the building or, even worse, they may become lost and unable to evacuate before being overcome by the hazardous conditions. However, this occurrence will not always be expressed within the results of the model as the occupants will not behave in this way unless it is explicitly stated in their behavioural sets.

Users of modelling tools have the ability of placing items within the building to recreate a realistic floor plan, for example, desks within an office or chairs within a reception. However, the location and number of items within the model may not represent the real life location within the building. Below is a section of the William Rankine Building floor plan (University of Edinburgh), where in the original plans the area by the stairwell is meant to be left empty to create a refuge area for occupants during an evacuation (Figure 41). However, currently it is being used as waiting area for the offices and has four chairs and a table in the way, thus diminishing the possibility for the area to be used for its original purpose.

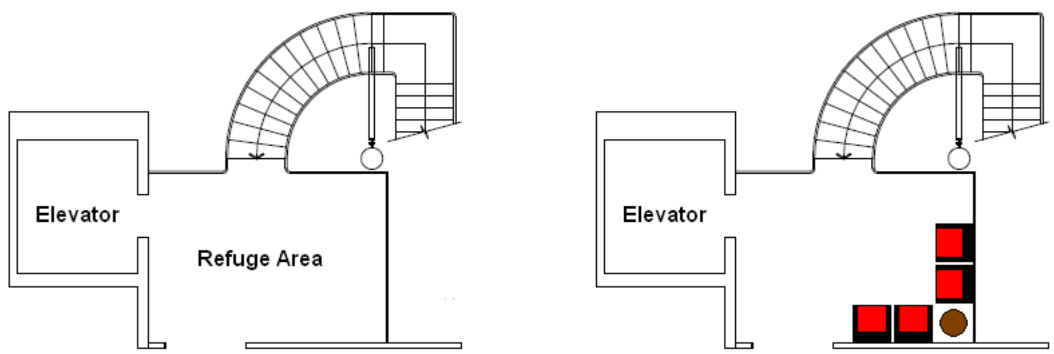


Figure 41: Example of model vs. real life

The movement/placement of furniture within a building are problems that the user does not have any control over. However, when testing the model the user should set up a scenario where certain exits or corridors are affected by furniture to see if it has a critical effect on the evacuation times.

The final geometric factor is the assumption users make about the elements along the egress paths and how occupants use them. Examples include the types of doors used, stairwells, etc. The first element is the use of double doors for an exit solution. The computer model may assume (unless stated by the user) that the occupants will use both doors to exit the building. However, it has been shown that the occupants will tend to only use one of the doors to exit the building [76], effectively halving the flow from the exit. Stairwells can significantly affect movement of occupants simply by alteration of the number of steps, the gradient of the stairs, location of handrails, etc. Proulx [77] states that stairway movement involves a complex set of behaviours, which include resting, investigation and communication. Most models will not have a behavioural set specifically for occupants using the stairs but instead will have a factor that will change the movement speed along the stairs affecting the evacuation results.

6.4.2 Training/Knowledge of the occupants

The level of training and knowledge of the occupants within an evacuation can drastically affect how efficient the overall evacuation process will be. However, evacuation modelling tools are limited in the amount of information a programmer can apply to a model when considering the previous training occupants may have. Therefore, a programmer is required to define specific behavioural aspects of an occupant before the simulation is conducted. This means the programmer must first make an important decision about the background of the occupants within the model and then program the model accordingly. However, the background information on how training affects an occupant's decision process is limited as it is obtained from experimental studies and interviews conducted after a real life scenario. Experimental studies do not produce the level of stresses felt within an actual evacuation, making the decision process easier, and unless the interview is conducted straight after a real fire, people will tend to forget why they made certain decisions.

In the majority of situations the public will look to a person of authority for advice during an emergency [75] and will wait to react based upon the actions of the staff members. Hence, staff members are required to undertake mandatory training on the safety procedures in order to understand their roll during an emergency scenario.

Within certain modelling scenarios it is important for the programmer to create a realistic behavioural set of actions based upon the training the staff members are required to have. However, occasionally during an emergency scenario staff members will forget their training and rely on others for guidance.

Therefore, it is important to assign occupants with certain behaviours (investigate the fire, warn occupants, activate the alarms, etc) whilst having a possible outcome of having the staff member "forget" part of their training and substitute in a new behaviour.

Non staff members can be categorised into one of two broad occupant groups, the leaders and the followers. Occupants will often adopt one of these behaviours during an evacuation scenario. The determination of which role a person will adopt can often be associated with either their level of knowledge or their prior experience with an evacuation.

An occupant with extensive knowledge of a building will move more efficiently through the building towards exits and will be able to make more effective decisions during a stressful situation. Also, prior experience of being within a real-life evacuation will alter the mind-set of a person and change the way they assess and deal with the situation. These occupants tend to become the "leaders" during the evacuation and others become the "followers".

Perhaps the greatest piece of knowledge an occupant can have is the location of and distance to not just the main entrances, but, also to emergency exits within the building. Often people who are not familiar with the building will try to head back towards the exit through which they entered. Meaning they may choose to walk a significant distance from their location instead of using nearby exits, increasing the overall evacuation time and increasing the potential of being exposed to hazardous conditions.

It is up to the modeller to decide how the program defines and distinguishes the leaders from the followers. If the model has too many leaders, then the evacuation time and flow paths will be quick and efficient (unrealistic); if the model has not enough leaders, people will take longer to evacuate, emergency exits will not be used or people will just wait in the building till they are told to evacuate, increasing the evacuation time.

6.4.3 Environmental factors within the building

The involvement of environmental factors can be difficult to incorporate within a human behaviour model. This is because it has been difficult for researchers to gather knowledge on how people actually react in real scenarios. Most models are created based on data from evacuation experiments or post-fire reports.

A model, in order to be as realistic as possible, needs to show how the occupants would react to the effects of heat, toxic and irritant gases and smoke. These environmental factors will have an effect on the occupant's ability to navigate through the building and the decisions they will make.

Smoke is the most common environmental factor used within a human behaviour model. Researchers [78] conclude that smoke can perform the following functions during an evacuation:

Alerts the occupants to an emergency
Inhibit the use of exit routes
Reduce speed due to lack of visibility
Irritation of the occupant's lungs and eyes (Reduction in speed and increased chance of getting lost).
Expose people to narcotic irritant gases and heat (Reduction in speed and increased chance of getting lost).

Table 13: Effects of smoke during an evacuation

The programmer can define how the occupants will react to an environmental factor within the behavioural set. The behaviours include: investigate, avoid smoke, wait for rescue, etc. However, the behavioural set will be based upon how the programmer thinks the occupants will react and this is where the error may occur within the results. Programmers need to make sure that occupants react to the smoke without reacting too efficiently. Most occupants, when they see smoke, will investigate in order to confirm whether or not there is cause for alarm. This process takes time as it involves a series of decisions (including: investigate, analyse, assess, activate alarm, etc.) and is very complex. Most models will allow the user to assign time values and probabilities to each action removing the "human" aspect of the process. Hence, if the programmer makes the occupant too efficient at the decision process (high probability of reaction and shorter reaction times) they will take less time to start evacuation, and vice-versa.

6.4.4 Behaviour of the occupants

The results produced by an egress model are highly dependent on the behavioural aspect of the occupants. As previously stated, the way a programmer defines the behaviours of the occupants has a major effect on the reliability of the model.

Creating a behavioural set for the model is complex as it requires the programmer to try and simulate the human mind in a series of probability distributions and mathematical formulae. These simulations need to include group and social affiliations between the occupants, the adoption of specific roles during the evacuation, responses to an emergency, travel speeds, making of decisions and the ability to carry out actions.

An important aspect of an occupant's behaviour is their perception of danger. This involves the process of how a person will assess a cue that alerts them to danger and if they will accept this as a serious cue to facilitate evacuation. Unfortunately, most models do not give the programmers the ability to define these specific kinds of behaviour within a model. Therefore, often programmers will use a delay time and specific occupant's speeds to model certain occupants within a building. This approach is also used to model the differences between the genders and age of the occupants.

6.5 Requirements for the I.D.E.S. System

As described in Section 6.4, the current generation of modelling tools are affected by the geometry of the building, the knowledge of the occupants, the environmental factors and the behaviour of the occupants as part of the attempt predict an evacuation.

The I.D.E.S. will require the use of a modelling program that can perform a wide range of functions needed by the system. Due to time constraints and budget limits it was determined at the being of this project that it would be more practical to use an existing modelling program than to create one from scratch.

The model chosen to be used for the Information Driven Evacuation System will have the following abilities:

Ability	Description
Evacuation Modelling	The program will be required to model the evacuation of occupants within a building and will need to include behavioural functionalities that will include the ability to demonstrate how the behaviour of the occupants will be affected by such activates/changes as activation of an alarm, the fire and how they will determine which exit and egress path to use. It will also need to be able to predict the behaviours the occupant might display during an evacuation, as well have the ability to integrate the information provided by the fire models as a way to influence the behaviours.
Fire Modelling	The program will need to have some sort of ability to predict the consequences of a developing fire either using a zone model style approach or using computational fluid dynamics. The results must be able to be integrated into the evacuation model to ensure that the occupants are affected/influenced by the development of the fire and the changing environmental conditions due to its development.
Integration of Live Sensor Data	This is the fundamental function that the modelling program will need to be able to perform. The I.D.E.S. will provide the occupant population with live information on the development of the fire and the safest egress route to take. Hence, the model will need to have up-to-date information itself.
Open Source	As the modelling tool will not be created from scratch and

Code	the likelihood it will be able to perform as required within the system, a program with an open source code would be ideal as it will give the capacity for the researcher to code new functionalities to create a more robust and appropriate tool for this thesis.

Table 14: Requirements for the System

Of course the program chosen will need to have its functionalities validated by experiments conducted by its creator or data gathered from real-life evacuation scenarios. Based on the above a selection of modelling tools was researched and their usability was assessed for the functions required for this thesis.

6.6 Review of Possible Modelling Programs

The new stage of choosing the modelling program to be used as part of the I.D.E.S. was determined using a simple office evacuation from a two storey building that was provided with two stairwells. The two programs chosen for the test were Fire Dynamics Simulator with Evacuation (FDS+Evac) and CRISP.

It should be noted that the modelling programs STEPS, EVACNET 4 and Pathfinder were also considered to be used as part of the system but due to their limited functionality (lack of fire development prediction and human behaviour sets) and the fact they are better suited for post fire evacuation models they were quickly disregarded as a possible model tool.

6.6.1 Fire Dynamics Simulator with Evacuation

FDS+Evac is a modelling program that was developed by Timo Korhonen and Simo Hostikka at VTT in Finland [79]. The program is a human behaviour evacuation simulation module that can be used to simulate fire development and the evacuation process. It can also be used to simulate an evacuation without the influence of a fire.

The core of the FDS+Evac modelling program is built around the use of a Fluid Dynamic Simulator as the coding structure. This structure uses a series of algorithms developed by the National Institute of Standards and Technology (NIST) that uses Computational Fluid Dynamics (CFD) to model the development of a fire based on the input parameters dictated by the user. It can be used to determine visibility due to smoke within a building, the Fractional Effective Dose of thermal and Carbon Monoxide gases and the activation of detectors and/or sprinklers.

Each person with a model is known as an agent which is assigned its own basic behaviours and exit strategies. Movement of each occupant is simulated with a two-dimensional plane that represents the floors of a structure. At each time step a basic algorithm of equation for motion is solved in order to model the movement within the space. As part of the movement, agents are programmed to responded to forces acting upon them that consists of physical, i.e. contact forces or gravity, and psychological created by the environment and other occupants.

The evacuation side of the program is stochastic, meaning it uses random numbers to generate the initial position and properties of the agents. This allowed for the ability to run several iterations of an evacuation to gain a wide range of data that could be used to analyse the behaviours of the occupants.

Details of the program's agent movement model and how it models the fire and human interactions can be found within the Technical Reference and User's Guide [79] as well as verification data used to test the coding and validate the model. However, these details will not be discussed as part of this thesis. Below the abilities for the use with the I.D.E.S. as well as the programs limitations will be discussed.

6.6.2 Abilities and Limitations

At the time of using this modelling program (September 2009) it was stated within the technical manual [79] that all the intended features of the program were not fully functional and that for now is it best suited for doing evacuation in a building where the floors are mainly horizontal, i.e. non-complex geometries. It also stated that the default staircase algorithm was very simple and should not be trusted too much if the stairs in the model get crowded, yet, it was claimed that the merging flows in each stair where restricted by the exit doors.

The model, in addition to creating the required meshes to model the fire development, would also need to create its own 2D evacuation meshes slowing down the simulation time of the model. This grid did not support time dependent geometries, i.e. the creation and removal of doors, which could be simulated as part of the fire modelling tool. There was also a restriction of the initial density of the agents and was limited to 4 persons per square metre.

The limitations that are stated with the user manual include the following:

Limitations	Description
Geometry	Efficiency of FDS is improved with the use of simplistic rectilinear numerical meshes which mean the geometric features need to confirm to a rectangular mesh. This means that the same limitations apply to the evacuation part of the code, meaning that items such as stairs or inclines are simplified.
Reduced Visibility	The smoke concentration derived from the FDS calculations will slow down the walking speeds of the occupants. However, the coding uses results from two laboratory run experiments, which often do not simulate real life effect very well. Hence the present version of the program uses an average value for each occupant, but, does not include an option for them to turn back when the smoke concentration is too high.

Incapacitation	The version of the program used could not model the effects of the HCN nor the toxic effects of CO_2, hence, occupants not be incapacitated by the effects of the smoke within the model.
Exit Route Selection	The coding used for exit route selection is simplified so that it does not include any kind of social interactions (herding behaviour). Hence, the user has the control over which doors are used by the occupants, thus, the evacuation is dictated by the modeller.
Detection and Reaction time	One of the most important factors of an evacuation, the pre-movement time, is decided by the user input that is determined by a chosen distribution of the detection and reaction times. Fire detection of the occupant cannot be connected to the activation of detectors within the FDS calculations, and hence the fire cannot trigger the movement/evacuation process.

Table 15: FDS+Evac Limitations [79]

The major appeal of the program is its use of FDS to calculate the effect of the fire on the occupants during an evacuation. As a prediction tool, FDS is a far more superior, compared to zone models, and robust method of predicting the development of a fire during an emergency. However, the issue with using the FDS is that it uses very complex algorithms that require a lot of time and computational power to run to make its predictions. In order to be used as part of the I.D.E.S. the predictions made by the model need to occur significantly quicker than the actual developments of the fire and it is unknown whether or not readily available technology (at an affordable cost) would have the power to run FDS simulations at the required speed.

A key function that the program will need to have is the ability to be able to assimilate input data gathered from sensors in real-time for both the prediction of fire development and the occupants' behaviours. FDS has been shown in the past that it can be updated using sensor input data (gathered from post processing analysis) to influence its prediction development. Yet, FDS+Evac does not have this capability at this stage within its development. However, FDS+Evac has open source coding giving a user the ability to create a coding script to provide this functionality, which is a strong positive for including this program within the system.

The behaviour of the occupants within the program is based upon the Panic model developed by professors from Dresden Technical University and Eötvös University in Budapest, which uses the basic principle that when an alarm is sounded all occupants will tend to demonstrate behaviours induced by panic (which include crowd stampedes) and will basically present selfish behaviour, i.e. it's each person for themselves. This behaviour, while it does occur occasionally, is not often seen during an evacuation and therefore basing the development of the movement algorithm on this type of model would not be justifiable for use in predicting the occupants' movements as part of the I.D.E.S. It also appears that during the simple office evacuation used to test the program that the occupants did not interact very well with the environment or each other. This was concluded to be due to the use of agent based movement algorithms that simulated that occupant interactions as water drops rather than actual humans.

6.6.3 CRISP (Computation of Risk Indices by Simulations Procedures)

CRISP is a modelling program that was developed by Dr J. N. Fraser-Mitchell at the BRE (Building Research Establishment) and has been in development over a significant time period. It has been used in projects such as the FireGrid project conducted by the University of Edinburgh in 2006 [10]. The program is a human behaviour model that is intended for research and evaluation purposes only; therefore, it has not been developed to be used in any commercial engineering designs.

The core of the CRISP modelling program is built around the use of a Monte Carlo controller. This controller is programmed to handle all of the inputs and outputs for each scenario, while at the same time controlling the initialisation for each model run. CRSIP uses a two-layer zone model to calculate the smoke flow for multiple rooms and also incorporates a detailed model for predicating human behaviour and movement. To ensure that the program is efficient, accurate and stable, the Monte Carlo controller uses an iterative approach for the required calculations in a scenario at variable time intervals while supervising all the physical inputs, i.e. fire growth and occupant's movement, are performing as intended for each time step.

The program uses sub-models to represent physical objects within a scenario, for example; rooms, hot smoke layers, and occupants. Due to the Monte Carlo approach, the program has been set up to randomise the starting conditions, which include the number, type and location of occupants within the scenario and the location of the fire and the type of objects burning. Vent flows are used to create the smoke flow between the rooms, where the flow is derived from the pressures arising from the difference in buoyancy between the two rooms. During the model operation these flows may form vent plumes, leading to further mixing of the gas layers in the room they flow into. The exposure and effects of smoke and narcotic gases on the occupants is tracked by the fractional effective dose (FED); when the value of FED reaches 1.0 they are assumed to be incapacitated.

The program uses the grid based approach to create a 'contour map' for each room in order to model the movement of occupants through the scenario. The layout of the room within the scenario determines the grid, where the shape of the room is stored as a polyline with a current limit of 20 corners. The walls are assumed to be vertical, with the floor and the ceiling of a room assumed to be horizontal planes that can be inclined to provide stairs or ramps.

The movement of the occupants through the network rooms within the scenario is defined using a route that is interactively calculated at each time step. The choice of route is affected by how easy the doors are to open and the walking distance, where the ease of movement through the door can be affected by the presence of smoke, or, prior to the simulation, directly by the engineer. CRISP uses a grid based approach to automatically create a 'contour map' for each room that directs the movement of the occupant to the next door within the route based upon on the distance and the obstacles' layout. Crowd densities will cause the walking speed to reduce, therefore, the program can change the path an occupant takes through a room to avoid areas of high crowd density.

CRISP is one of the few modelling programs that attempts to calculate the occupants "pre-movement time", rather than use an empirical distribution, in term of the delays associated with various pre-movement actions performed in response to early fire cues. These action include investigate, warn others and attempt to put out the fire. However, if the occupant actions do not actually require them to move, then all these actions can be combined into a single delay in reacting to the alarm.

The behavioural coding within CRISP uses a series of actions to describe the occupant's behaviour during the scenario. It assumes that each occupant will adopt distinct behavioural roles, either naturally or due to training. An action may be abandoned and changed to a new one based upon the state of the surrounding environment and current knowledge, which may of course be limited and/or incorrect. CRISP automatically chooses the occupant's destination according to the action being performed. Therefore, the assigned behavioural role for each occupant will determine their individual responses and actions during an emergency evacuation.

According to the creator, “The idea of an action that requires the occupant to go somewhere and then do something is the key concept behind the behavioural rules used in CRISP”. Hence, there is a period of time for which the occupants must wait before the action is completed. Therefore, if the action takes longer than the allocated time, the action will be dropped and a new action will be substituted in its place. An engineer can create and assign more than one behaviour set of actions to the occupants within the simulation, for example, one set could be assigned to a leader and the other could be assigned a lead profile.

The start location of the occupants is randomised by CRISP based on the probabilities and the time of the evacuation, using the scenario fire start time to select and randomise the data for an occupant. The person’s occupant data also states the values for movement speed and head heights, which will affect how quickly each occupant fraction of FEDco increases, based on a normal or log-normal distribution.

6.6.4 Chosen Modelling Tool

The human behavioural model CRISP was chosen as the main modelling tool of this PhD for the following reasons. Firstly, compared to FDS+Evac, CRISP had a very adaptable and more robust human behavioural model that can be easily understood and altered by the programmer. Secondly, CRISP had been validated far more extensively compared to FDS+Evac and therefore has more detailed behavioural sets that can be assigned to each of the occupants. Thirdly, Dr Sung-Han Koo [57] has altered the CRISP program to create a version where information from sensors can be imported live into the model to create a sensor-steered simulation that can predict the evolution of fire emergencies. Following his coding structure and development of the program it would be a relatively simple procedure to implement live sensor data to steer the egress simulations. It should be noted that both programs were provided with an open source code that allowed for models to be updated/altered as required for the I.D.E.S. so it could be possible to do the same with the FDS+Evac tool.

A reason for choosing FDS+Evac instead of CRISP for the system would be its implementation of computation fluid dynamics to model a fire rather than CRISP's zone model technique. CFD (Computation Fluid Dynamics) is a far more robust and accurate method to model the consequences of a fire within a building and is a better tool to show how the smoke would move through egress corridors and affect the occupants. However, this style of model takes far longer to complete and requires a significant increase in the system requirements of the modelling machine. Whereas, zone models can efficiently run on most computers and take significantly less time to produce results. This is because zone models redistribute the mass/energy from the fire around a defined space amongst only a few zones or cells (two layers per room), whereas, FDS (as a CFD model) uses a much larger number of zones/cells, giving greater spatial resolution but with a significantly higher computational expense and more detailed input. These are reasons why the zone model was chosen over using the fluid dynamic model.

6.7 Summary

In summary, this chapter has focused on the purpose of prediction models within the fire engineering field, which includes the simulation of a fire emergency situation for analysis and their use as part of the research and development used to further the knowledge of engineers within the fire engineering field.

A brief historical development of the mathematical algorithms and process used as part of the early predication models was broken down and included techniques such as the network-node analysis, nodal step method, cellular automata models and agent-based models.

The limitations of prediction models were discussed within the chapter which addressed the difficulty of determining the data needed to create the models and deficiencies in the representation of human responses/ behaviours [70][71].

Building on the discussion about the limitations of prediction models, four factors were identified as relying heavily on a user's input to produce results. These include: the geometry of the building, the training/knowledge of the occupants, environmental factors within the building and the behaviour of the occupants. The level of involvement with which each of these factors is represented within a program varies in complexity from one model to the next and this was used to help to choose the programs that would be used as part of the system.

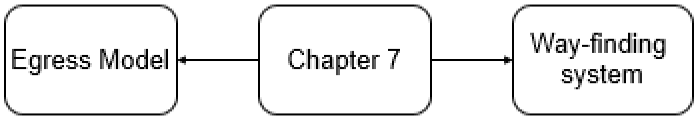
It was determined that the program chosen for the system would need to be able to perform a wide range of functions in order to provide updated information to the occupants during an evacuation. As discussed, due to time and budget constraints it was more feasible to use an existing modelling program than to build one from scratch. The chosen tool was required to be able to conduct prediction models for both the evacuation of the occupants and the development of the fire, while having the ability to assimilate information from sensors in real time and incorporate them into the prediction models. As part of the development of these models it would be necessary to have a program with an open source code so that it could be altered as needed to either improve its functionality or allow for further additions to be made.

Out of the available modelling tools used by fire engineers two were chosen for further testing based on the requirements outlined in Section 6.5, which were FDS+Evac and CRISP.

The model eventually chosen to be used as part of the I.D.E.S. was the human behavioural zone model CRISP as it had a very adaptable and more robust human behavioural model that was developed more extensively compared to FDS+Evac. It was also proven to be able to assimilate live data from sensors and then predict the development of fire in real time. As the program is a zone model the predictions made would be less detailed these that from the FDS+Evac program (which uses CFD); however, given this, it would result in significantly shorter simulation run times and reduce system requirements for the hardware.

The following chapter will focus on the three experiments conducted as part of this thesis and the empirical data that was gathered, with a description as to why it was necessary to obtain this information for the development of the Information Driven Evacuation System.

7 Empirical Data / Experiments



The following chapter covers the empirical data required as part of the development of the Information Driven Evacuation System and the experiment that were conducted. It also details the involvement of the author within each experiment and the analysis of each experiment that was conducted and the data obtained.

7.1 Data requirements & Current Data Omissions

In order to develop the current version of CRISP to be used as part of the I.D.E.S. firstly we have to ensure that the current version's human behavioural prediction capabilities are well developed. The fire prediction capabilities of CRISP have already been demonstrated by Dr Koo as part of his thesis [12]. There is a large amount of information on the behaviours of occupants during emergencies, yet, the detail necessary to be able to modify CRISP was not available. This was apparent within the initial stages of the development of the ideas behind the system when researching into occupants behaviours in reference to way-finding tools. Data on the influence of way-finding tools on exit choices and egress paths was limited and did not have the level of detail needed to successfully update CRISP nor did it allow for a detailed comparison.

Most research papers will provide the reader with an average walking speed and the number of occupants who used a specific exit with some detail on the behaviours of occupants. Yet, they do not record the movement choices of the occupants and how they interact with each other and the environment. The phenomenon of social interactions, including information sharing and learning effects, are vital to the success of the system. It is apparent that during real-life emergencies people would often talk about the situation or look to others for guidance and information [28]. As the system is a new approach to an evacuation compared to the current methods used (alarms and passive signs), if one occupant was able to decipher the purpose of the audio and visual tool the information provided would be more likely to be shared and followed. Hence, understanding of social interactions will be required to help focus the development of the I.D.E.S. and the choice of way-finding tools to use.

The choice of way-finding tools to use as part of the I.D.E.S. system will be determined on their ability to influence the occupants' exits choices. There is data currently available that shows the influence of way-finding tools on occupants that provide positive data [27], for example green lights or a voice message guiding occupants to a specific exit. Conversely there is no information of tools that provide negative data, for example red lights or a voice message warning occupants form using a specific exit. Nor if providing a combination of positive and negative data would produce the desired result for the system.

7.2 Overview of Trials

As part of the development of the I.D.E.S., three series of evacuation experiments were conducted to obtain the data need as described above with the fundamental goal of using the newly updated computer egress model to conduct a feasibility study as part of this thesis.

The feasibility study will be used to see if the prediction capabilities of the updated CRISP model are able to demonstrate realistic behaviour patterns and exit choices of the occupants within a high rise building compared to that observed during the experiments. It will also be used to compare the flow rate, overall evacuation time and behaviour of a large group of occupants over a series of emergency scenarios.

The first of the experiments was conducted within the laboratory at the University of Lund, Sweden.

7.2.1 Experimental Series 1

In a fire, the process of evacuation can be confusing and stressful due to the lack of information provided about the fire and/or evacuation procedure/egress routes. If a fire was to occur on a passenger train travelling in an underground rail system it is understood what factors might influence performance, however, it is unknown how the passengers will respond to the fire stimuli. The general principle for the evacuation is to move the train to the nearest station and have the passengers disembark [80]. This is the ideal situation; however, it will not always be possible and the passengers sometimes are required to evacuate from the train inside the tunnel [81].

There are many factors within the tunnel and train that may affect the evacuation process. These include the exit height from train to tunnel floor, the flow direction within the tunnel, the number of occupants within the tunnel and on the train, the obstructions within the tunnel and the lighting conditions inside the tunnel. For the development and testing of the I.D.E.S., Experiment 1 was conducted to study the behaviour of the occupants to see how they would react to the repeating of a test and the effects of learning on their exit strategy and confidence during the evacuation. The first experiment was conducted to study these factors as part of the METRO project [57].

METRO is a research project focusing on infrastructure protection led by the Fire engineering team at the University of Lund in Sweden [57]. The project is concerned with infrastructure protection, mainly the protection of underground rail mass transport systems. It will also have a secondary focus on fire and explosion hazards, evacuation, rescue operations and smoke control.

The second experiment conducted was also a part of the METRO research project and was conducted within an abandoned construction tunnel in Stockholm, Sweden.

7.2.2 Experimental Series 2

Tunnel fires, whether road or rail, can have significant repercussions when it comes to structural damage, cf. the Channel Tunnel fire [82], and human preservation, cf. Baku subway fire [83]. The effects of smoke within a tunnel can be significantly more potent to an occupant due to the closed environmental space, lack of natural ventilation and the energy from the fire that is retained within the tunnel. The environment of the tunnel is often not familiar to the occupants; hence, they will rely on staff to guide them during an emergency. Unfortunately, the majority of the time there is a high possibility that the staff are not on site to provide help in the early stages and may be unable to help during the spread of fire or smoke. Hence, it is important to ensure that the evacuation of both the staff and passengers from the tunnel fire situation is as efficient as possible.

To study possible solutions to increase the efficiency of a tunnel evacuation an experiment was conducted as part of project METRO led by the Fire engineering team at the University of Lund in Sweden [84]. The experiment was held in May 2011 and was described as the second stage experiment under work package 2.

These experiments are referred to as the “medium-scale experiments” on the project METRO website [84] and were conducted to examine the overall effectiveness of different way-finding evacuation tools on an occupant decision process and flow rate within a smoke-filled tunnel. Participants were asked to take part in an experiment where they had to negotiate a smoke-filled tunnel and find the exit out of the tunnel.

The objectives of the experiments were to find the effectiveness of different way-finding equipment and, to study the behaviour of the participants and their walking speeds. This was necessary to help develop the coding to be used within the CRISP modelling program.

The final experiment conducted took the information gathered from the first two experiments on the effects and ability of occupants to learn and how the interacted with the way-finding tools.

7.2.3 Experimental Series 3

During an evacuation from an emergency situation, evacuees will more often than not choose the exit that is most familiar to them as they expect that it will lead them to the outside and safety, and have prior knowledge of this route [85]. This exit is normally the main entrance to and from the building and not an emergency exit. This could be problematic during an evacuation as it may create a bottleneck or large queues if all occupants try to use the same exit [86]. Buildings are designed based upon a percentage of occupants using other emergency exits in order to evacuate the building before the available safe exit time is reached [87]. The purpose of this experiment was to determine whether it was possible to influence an occupant's exit choice, using way-finding tools, when the preferred route is unusable.

The relevant experiments consisted of two separate evacuation tests which were conducted at the University Of Edinburgh, Scotland, in 2011. The first experiment was conducted to calculate the flow rates and reaction time of occupants during a "normal" evacuation. The occupant's exit choices and behaviours were to be analysed. In the second experiment it was intended to analyse the same information as the first, however, the main stairwell would be rendered "unusable" by the occupants. The main objective of the second experiment was to see whether or not an occupant's exit choice can be influenced by the use of a combined visual and audio way-finding system.

This would be the final information needed to address the data currently not available to be used to develop the I.D.E.S. evacuation model.

7.3 Contribution of Each Trial

As previously outlined contributions came from both Lund and Edinburgh students in two of the experiments as they tool place as part of a joint venture.

7.3.1 Experiment Series 1 Contribution

As part of an exchange program initiated by the author, there was an agreement between Edinburgh and Lund to work alongside Mr Karl Fridolf and Dr Daniel Nilsson as part of their research team working on METRO for 6 months to help on the small and medium scale experiment.

The first task was to plan the experimental rigging for the small scale test and develop, alongside Dr.Fridolf, the different scenarios to be tested during the experiment. While Dr.Fridolf was sourcing the spare train parts to be used in the rigging and how to gather the required amount of students for the tests, it was the author's job to analyse a common Stockholm METRO rail cart and design a rigging that used aluminium frame to recreate a Carriage and Tunnel within the lab space at Lund University.

Once the materials were sourced, it was up to the two PhD students to build and paint the rigging to simulate that of a real tunnel on an as near a reasonable practicable basis. This included the installation of the lighting, movable floor and camera to capture the required data.

On the day of the experiment it was the author's task to guide the occupants to the experimental rigging and to gather all experiment footage once each test run was completed.

The data was then separately analysed by both students and compared to ensure both data sets were producing similar results. Analysis of my data was carried out within the offices at Edinburgh University.

7.3.2 Experiment Series 2 Contribution

Due to being located within Edinburgh during the brain storming stage of the medium scale experiment, I was consulted for advice on the experimental rigging and data to be gathered via emails between the two Universities. I was asked to help with the conduction of the experiments, where it was my task to upload the information from the thermal camera used by the fire service to film the occupants within the tunnel as they evacuated, as well as maintain the smoke and acetic acid levels within the tunnel.

The raw experimental data was analysed by the University of Lund and I was given access to their results to use as part of my models and code development, as agreed upon between the two universities. This was in due part to the ethical agreement the University of Lund has to follow, where experimental videos of Swedish citizens are not to be distributed out of the country without their permission.

7.3.3 Experiment Series 3 Contribution

The final experiment conducted was solely designed and undertaken by myself with the input of my supervisor, Dr Stephen Welch. All experimental data gathering and analysis was also conducted fully by the author.

7.4 Experiment Series 1 - Stationary train to tunnel floor evacuation

As explained previously, the first experiment conducted was looking into the evacuation process from a train that has had to stop within a tunnel due to an emergency occurring. The experiment looked at the factors that could affect the evacuation process, which included the exit height from train to tunnel floor, the flow direction within the tunnel, the number of occupants within the tunnel and train, the obstructions within the tunnel and the lighting conditions inside the tunnel.

However, for the purpose of the I.D.E.S. development, the experiment allowed for a hands-on experience to study the behaviour of the occupants to see how they would react to the repeating of an experiment and the effects of learning on their exit strategy and confidence during the evacuation.

The following is the breakdown of the experiment and the analysis of the results gathered.

7.4.1 Small-scale rigging

The small-scale experiments were held within the lab at the University of Lund on the 3rd and 9th of December 2010. The design for the experimental rig used was based on the X1 Train, which is an older version of a subway train used by the Stockholm Metro, and the dimensions of the tunnels within the Stockholm Metro. The train and tunnel were combined in one rig in order to simulate an evacuation occurring in a tunnel environment (Table 16).

Dimensions (m)	Train	Train Lobby	Tunnel
Height	2.7	2.7	4.1
Width	2.31	2.31	0.85
Length	6.09	1.9	6.09

Table 16: Dimensions of experimental rigging

The interior of the rig was sourced from an old X1 train from a scrap metal yard near Nykroppa in the north of Sweden. The seats, luggage racks, handles and doors were obtained and installed within the rig. This produced a walking width of 0.71m and created an exit lobby with dimensions of 2.7m x 2.31m x 1.9m.

Due to the location of the train rig, within the lab, both the train and tunnel experienced a lot of natural lighting which was not desirable as the experiments where recreating a subway environment. To counteract this effect, rows of black curtains where installed at both entrances (tunnel and train), as a way to remove most of the light. Thus, the only light supplied within the tunnel was that required to meet the Swedish code illumination of 1 lux in the middle of the two emergency lights in the tunnel at ground level [88].

Seven cameras in total were installed within the experimental rig, three within the train and four within the tunnel (Figure 42). The three cameras in the train were installed to capture general human behaviour, the density within the lobby and the exit flow rate into the tunnel. The four cameras in the tunnel were used to capture exit strategies, learning effects and the flow rate through the tunnel.

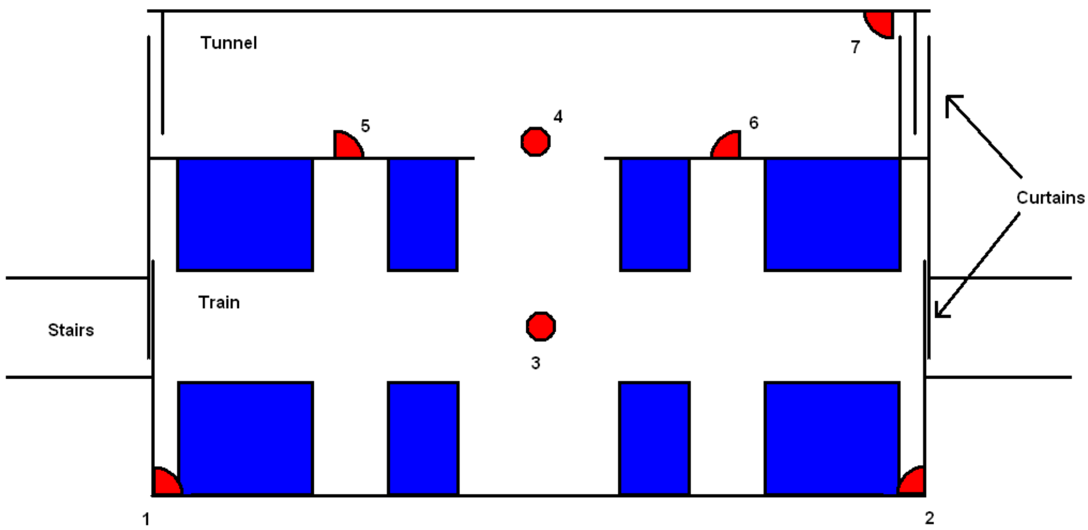


Figure 42: Location of the cameras within the experimental rigging

7.4.2 Test participants

Two different groups of participants were involved in the experiments on the 3rd and 9th of December with a total of 46 and 38 individuals respectively. The groups were composed of students from the engineering department (LTH) at Lund University, Erasmus exchange students and PhD students from the fire engineering department.

As can be seen in Table 17 the age range of the participants was between 18 and 40 years of age. Participant gender was roughly split 60/40 between men and women respectively. The selection of participants used does not represent the full demographic of people who daily use trains; however, as the experiments were conducted mainly to see how certain variants to the rig would affect the density and flows within the train and tunnel the participants group was considered acceptable.

Day	Age [years]				Number of Participants		
	Mean	Min	Max	Std.	Women	Men	Total
1	22.5	18	40	3.6	20	26	46
2	23.4	19	31	2.4	15	23	38
total	22.9	18	40	3.2	35	49	84

Table 17: Participants information

To simulate a real life train evacuation, the participants were not provided with protective clothing, but instead they wore their regular indoor clothes and shoes. However, as it was indoors the participants did not wear any jackets and as it was an experiment no one had brought luggage with them. Again, it is likely that these conditions are not reflective of actual transport conditions.

7.4.3 Test scenarios and variants

On each day of testing the participants were told that they were to take part in a series of evacuation experiments. In total, on both days, the participants took part in eight different experimental scenarios with a series of different variants in order to examine the effectiveness of the evacuation process (Table 18). It should be noted that the order of the experiments was not randomised due to time limitations.

Variants	Options	Description
Floor Height	Max	1.4 m for train to tunnel floor
	Mid	0.75m for train to tunnel floor
Ladder	Yes	Evacuation ladder used from train to tunnel floor
	No	No ladder is installed
Lighting Conditions	Standard	Two emergency lights inside the tunnel, providing a lux level of 1 at floor level outside train doors[88]
	Increased	Two LED spot lights underneath train exit; provides higher lux level within tunnel
	Lights Fail	During final experiment the train light were turned off to simulate battery failure of the train systems
Handles	Yes	3 vertical handles placed in exit lobby
	No	No vertical handles placed in exit lobby
Floor Material	Smooth	Concrete blocks
	Rough	Gravel stone found in Metro tunnel (20 – 30mm)

Table 18: List of test variants used during experiments.

Figure 43: Photos of the floor material, lighting configuration, evacuation ladder and handle arrangement

The scenarios were set up as follows, based on the day the experiments where held:

- 3rd of December – Smooth Concrete Block Floor
- 9th of December – Rough Gravel Stone Floor

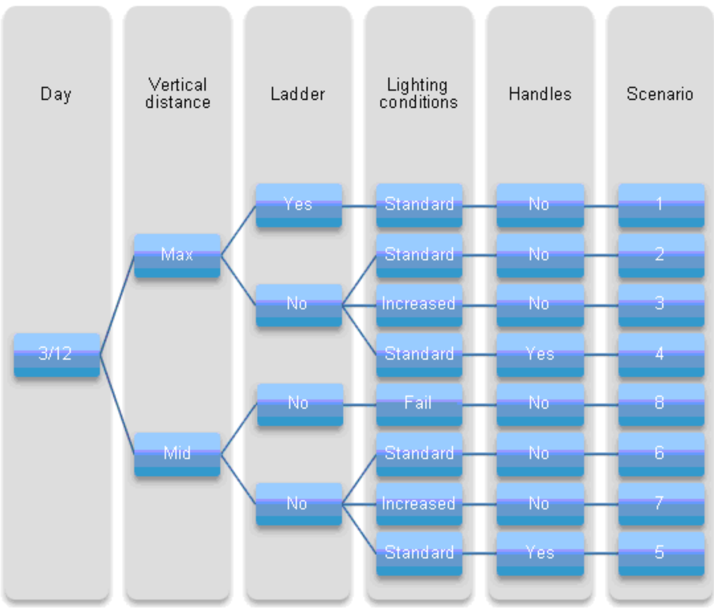


Figure 44: Eight variations of the experiments run on 3rd December (the scenario-number represents the order of the experiments)

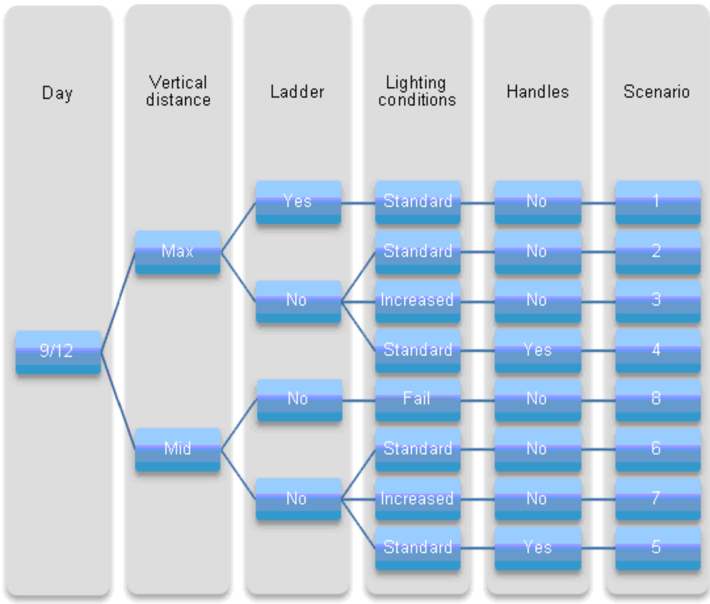


Figure 45: Eight variations of the experiments run on 9th December (the scenario-number represents the order of the experiments)

7.4.4 Experimental procedure

As seen above (Figure 44 & Figure 45), on each day of the experiments the occupants were put through various different experimental scenarios. The students were separated into two groups (A and B) and were sent to the corresponding entrances of the train. Five students from group A and five from group B were chosen to become group C (for each run different students were used) who would enter the tunnel from one side and walk through the tunnel to the other exit. This action was to simulate the flow of passengers in the tunnel who had evacuated from other exits further along the train (Figure 46).

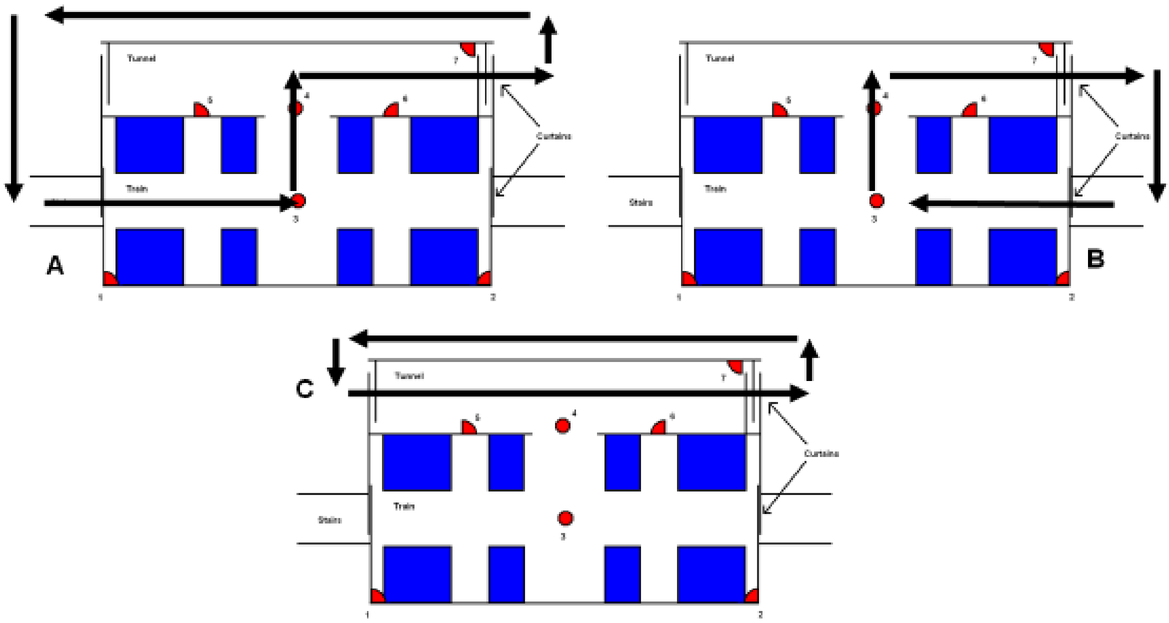


Figure 46: The flow paths of the three participant groups.

At the beginning of every experiment, eight students from A and B were told to enter the train and either stand or sit in the seats. At the sound of a single whistle the students were told to start evacuation from the train by any means they wanted to. After exiting the tunnel students were told to return to the assigned exit and re-enter the train until they heard two long whistles which signalled the end of the experiment. The experiments generally lasted for 5 minutes.

The students were led away back to classrooms while changes were made to the experimental rig during a 5 minute break. When changing the floor heights the students were given a 20 minute break while the concrete blocks were put into place.

The final scenario was an identical copy of scenario two, however, after 5 minutes, instead of stopping the experiment, the lights in the train were turned off to simulate a battery failure of the safety systems. The students were then required to continue to evacuate for a further 5 minutes in the dark.

7.4.5 Analysis of live evacuation data

For each of the experiments conducted, the densities of the participants within the train exit lobby and the flow rate through the train and tunnel were calculated. From analysis of the relevant recorded video footage from camera 3 (Figure 42) the densities (persons per square metre) were calculated using an area of 2.85 m^2 (length 1.9m by width 1.5m) and divided by the number of occupants found within that area at a 5 second interval and averaged over the whole experiment. The average densities for all eight experiments for both days are shown below in Table 19

Experiment	03-Dec-10 (p/m^2)	09-Dec-10 (p/m^2)
1	2.57	2.42
2	2.15	2.19
3	2.03	2.07
4	2.26	2.13
5	2.29	2.41
6	2.30	2.15
7	2.41	2.20
8	2.26	2.21

Table 19: Average Density for each experiment

From analysis of the relevant recorded video footage from camera 4, for the train, and camera 7, for the tunnel, the flow rates were determined by counting the number of occupants to pass through the tunnel and train exit at 30 second increments and averaged over the whole experiment, which can be found in Table 20 and Table 21.

Experiment	03-Dec-10 (p/s)	09-Dec-10 (p/s)
1	0.4552	0.561
2	0.7952	0.702
3	0.7994	0.712
4	0.7679	0.766

5	0.7606	0.767
6	0.8230	0.741
7	0.8224	0.794
8	0.7761	0.792

Table 20: Average tunnel flow rate for each experiment

Experiment	03-Dec-10 (p/s)	09-Dec-10 (p/s)
1	0.328	0.373
2	0.587	0.520
3	0.543	0.500
4	0.476	0.502
5	0.517	0.569
6	0.564	0.559
7	0.567	0.527
8	0.454	0.545

Table 21: Average tunnel flow rate for each experiment

To ensure that the straight line correlation used to calculate the flow rates fit the experimental data correctly the R^2 value for each data set was determined. With the R^2 value the closer it is to 1 the better the fit between the data and the line drawn through them. The closer the value is to 0 the worse the statistical correlation is between the data and the line. The R^2 value (often referred to as the goodness of fit) is computed using:

$$R^2 = 1 - \frac{\sum (Yi - Yi')^2}{\sum \left(Yi - \overline{Y}\right)^2}$$

Equation 1: Goodness of fit equation. [89]

"Where Yi represents an individual data point value, Yi' represents the value obtained by when the independent coordinate of this data point is input into the best-fit function (a line in this case). Therefore, Yi' represents the values of the data points projected onto the line of best fit (the ideal values). $\overline{Y}$ Represents the average of the Yi values." [89].

An example of the R^2 value for the data set can be found in Figure 47.

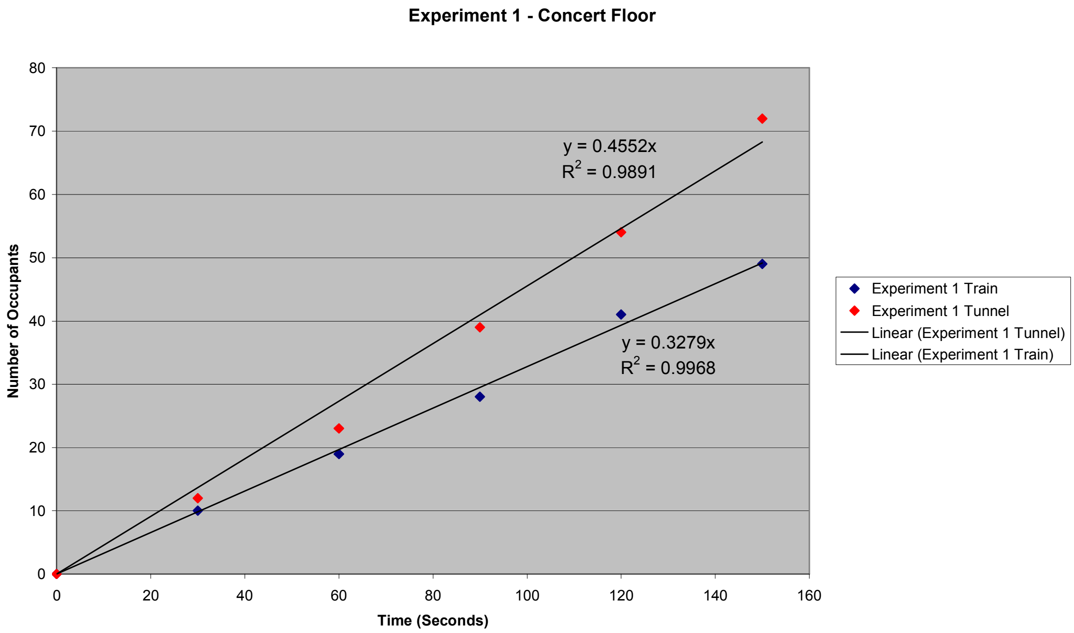


Figure 47: Example of the R^2 value for experiment 1 for the 3rd of December

Experiment	03-Dec-10 R^2		09-Dec-10 R^2	
	Tunnel	Train	Tunnel	Train
1	0.9891	0.9968	0.9755	0.9611
2	0.9996	0.992	0.9943	0.9995
3	0.9983	0.9995	0.9963	0.9985
4	0.9985	0.9919	0.9975	0.9991
5	0.9978	0.9980	0.9989	0.9996
6	0.9980	0.9974	0.9978	0.9995
7	0.9981	0.9938	0.9980	0.9998
8	0.9974	0.9927	0.9990	0.9988

Table 22: R^2 value of the flow for each experiment

As can be seen from Table 22, the R^2 values determined for each of the experiment were mostly above 0.99, meaning the fit between the line and the data set was statistically very strong. However, in order to compare the live data results to each other and to the results produced by a computer model the flow rates for the train and the tunnel must be standardised to per metre width. Therefore, the average flows for the train and the tunnel are then divided by the width of the exits. (1.7m and 0.85 respectively) and are shown in Table 23 and Table 24 below.

Experiment	03-Dec-10 (p/s/m)	09-Dec-10 (p/s/m)
1	0.193	0.220
2	0.345	0.306
3	0.319	0.294
4	0.280	0.296
5	0.304	0.334
6	0.332	0.329
7	0.333	0.310
8	0.267	0.320

Table 23: Standardised average train flow rate for each experiment.

Experiment	03-Dec-10 (p/s/m)	09-Dec-10 (p/s/m)
1	0.536	0.660
2	0.936	0.826
3	0.940	0.837
4	0.903	0.901
5	0.895	0.902
6	0.968	0.871
7	0.968	0.934
8	0.913	0.932

Table 24: Standardised average tunnel flow rate for each experiment

7.4.6 Discussion & Conclusions

The peak density value calculated for experiment 1, as seen in Table 19, can be explained due to the effects of unfamiliarity of the experimental rig and testing experienced by the participants. It can be seen on the video that when the initial whistle is blown participants waited a significantly longer time to start evacuating than in other experiments. This was due to the participants waiting for someone to become the leader and start the evacuation, which is a basic human behavioural trait where people do not want to be embarrassed in front of their peers [90]. The slight increase in value at experiment 5 could have been due to the change of evacuation height from 1.4m to 0.75m, which in turn would have altered the participant's evacuation technique they had used during the first four experiments as the drop became significantly more difficult. However, overall it appears that the variants did not have a very significant effect on the densities calculated from the live data (excluding experiment 2 and 5).

The low flow rate within the tunnel and train observed in experiment 1 on both dates can be assigned to the effects of unfamiliarity of the participants with the experiment, as experienced in the densities. The occupants did wait significantly longer to start the evacuation than in the other experiment and also waited longer to evacuate from the train to tunnel floor. This could be due to the fact that in the initial experiment the participants were unsure as to what method to use to evacuate and as they repeated the experiment they were able to refine their technique to evacuate the train more effectively.

The reliability of the results produced by the live evacuation may include certain issues; for example, differences that might exist in the behavioural response from these participants and those exhibited in a real situation. It is possible that the occupants were more calm and relaxed as they were given relevant information prior to the experiments and hence were well informed, which will not be the case in most real world evacuations. They may also be more willing to wait and make room for others to pass, as they are aware that they are not at any immediate threat from fire or smoke. Another issue is that the reliability of the results will have been affected by the repetition of the experiment. It is natural that the more frequently a person is introduced to a given test environment the more comfortable they become, thus reducing their urgency to evacuate. Finally, the occupants will tend to develop effective exit strategies that they will continue to use over and over again in the experiments. This would not occur within a real evacuation.

These issues may explain part of the lack of effect of the testing variants on the overall densities and flow rates of the small scale experiments.

7.5 Experiment Series 2 - Smoke-filled tunnel evacuation with various way-finding tools

The second experimental series in this thesis was conducted to examine the overall effectiveness of different way-finding evacuation tool on an occupant decision process and flow rate within a smoke-filled tunnel. The goal was to determine the effectiveness of different way-finding equipment by studying the behaviour of the participants and their walking speeds. This was necessary to help develop the coding using within the CRISP modelling program.

The following is the breakdown of the experiment and the analysis of the results gathered.

7.5.1 Experiment location and setup

The medium-scale experiments were held within an unused tunnel located in Stockholm, Sweden between the 30th of May and 1st of June 2011. The tunnels' original use was as an entrance tunnel for heavy equipment during the construction of the southern link motorway, after its construction the tunnel was closed off and is now used by the Stockholm Greater Fire Brigade for practising exercises.

The dimensions of the tunnel can be found in Table 25 and Figure 48 for the cross-section design plans. The tunnel has a gradient of -0.10 for the first 140m metres. For the evacuation experiments a 200 metre section of the tunnel was used, therefore, the gradient section was included.

	Dimensions (m)
Total Length:	200
Height:	8
Length of Slope:	140
Change in Elevation:	15

Table 25: Dimensions the of tunnel

7.5.2 Test participants

A total of one hundred participants took part in the experiments over the three days. The recruitment of the participants was through an advertisement placed on an online portal that is used by researchers to list possible experiments. Anyone who was interested in participating could apply online through the portal. The advertisement included a description of the experiment, details on the location and dates of the experiment, the payment offered and the time they were required to stay for. The participants were aware prior to agreeing to take part that the experiments involved walking through a tunnel in dense artificial smoke and that acetic acid would be used to create an irritating environment. However, they were not aware of any of the way-finding tools that were to be used during the experiment.

Restrictions were placed upon those who might participate. Occupants were required to undertake an Anxiety and Depression test and if they showed high levels for both they were not included in the experiment. Also, participants who were younger than 18, had problems with asthma or were involved in the field of fire safety (e.g. a fire fighter or fire safety engineer), were exempt from the experiments.

The participants who ended up taking part in the experiments ranged in age from 18 to 66 years and out of the 100 participants 56 were men and 44 were woman with a height range from 153 to 198 cm. The occupants were asked how frequently they used underground transportation and it was found that a significant major (89%) used the Metro at least once a week. Hence, they had prior knowledge and experience with underground transportation. A small percentage of the participants had received information about evacuating from a Metro system or read the emergency information posters in the trains or at the stations. Thus, we could assume that the occupants were not well informed on how to evacuate a tunnel during an emergency.

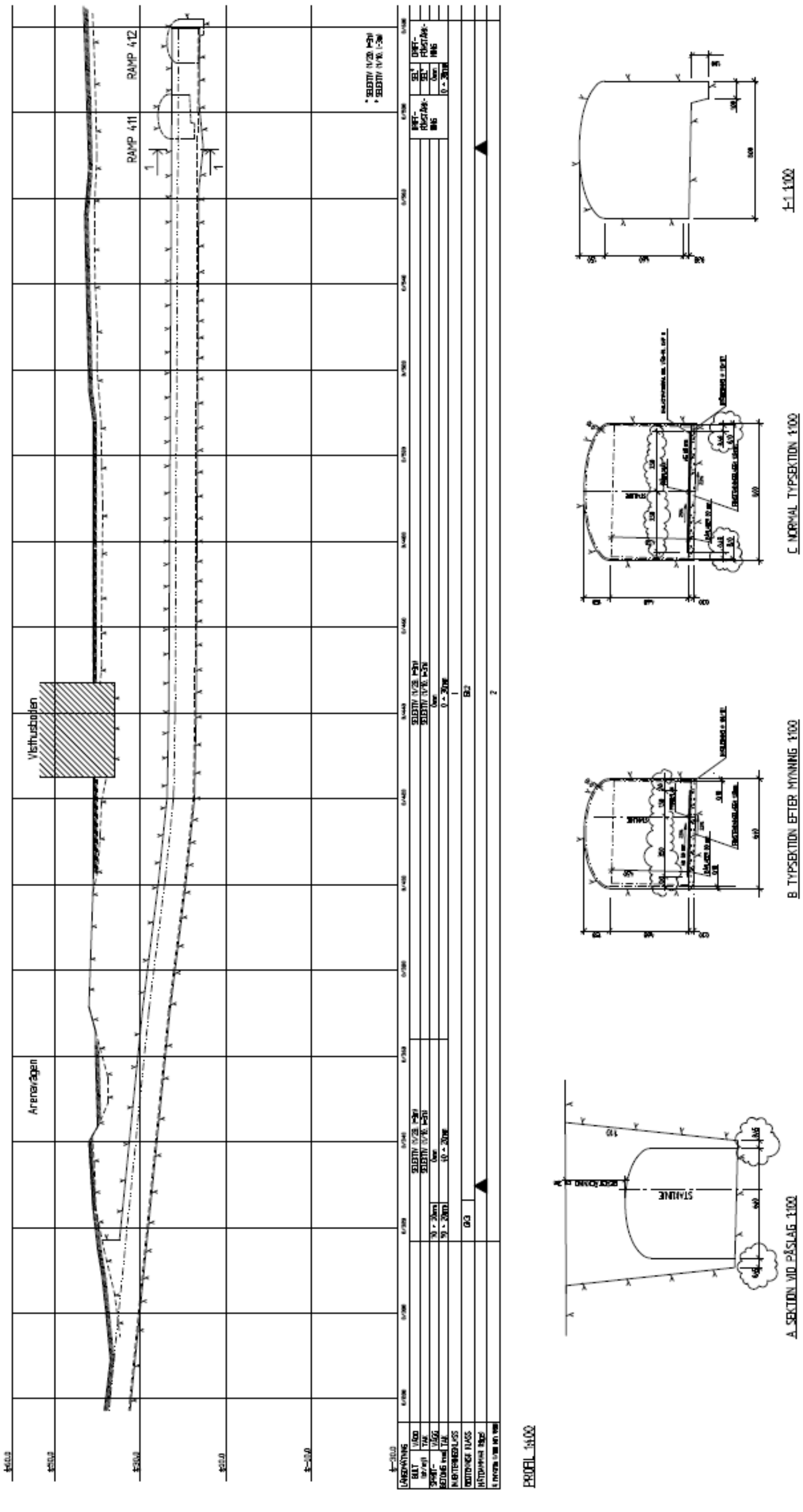


Figure 48: Cross-section of tunnel used in the experiments

7.5.3 Test scenarios and variants

The experiments were carried out within a 200m section of tunnel where the tunnel consisted of a 122 metre section with a gradient of 10% and a 76 metre section with no gradient. The floor surface was mostly smooth for the majority of the tunnel and consisted of compact gravel. A section of the tunnel about 150 metres into the tunnel (32 metres long by 1.5 metres wide) used a different floor material (gravel 32-64mm in size) in order to analyse a change of floor material on the movement speeds of the occupants.

Emergency signs were installed every 8 metres (Figure 49) along both sides of the tunnel at a height of 1 metre to recreate the feeling of being in a real Metro tunnel. The design of the signs were based on the current emergency signs used in the Stockholm Metro [88] and provided passengers with information on the distances to the nearest exit while providing lighting to the tunnel. In order to meet the Swedish requirements for emergency lighting within a tunnel the light intensity had to provide 1 lux at ground level between two signs [91].

Figure 49: Signage provided within tunnel

The exits from the tunnel consisted of a mock-up door installed 180 metres into the tunnel on the left hand side. The door was equipped with several different way-finding tools that were to be used through the testing period.

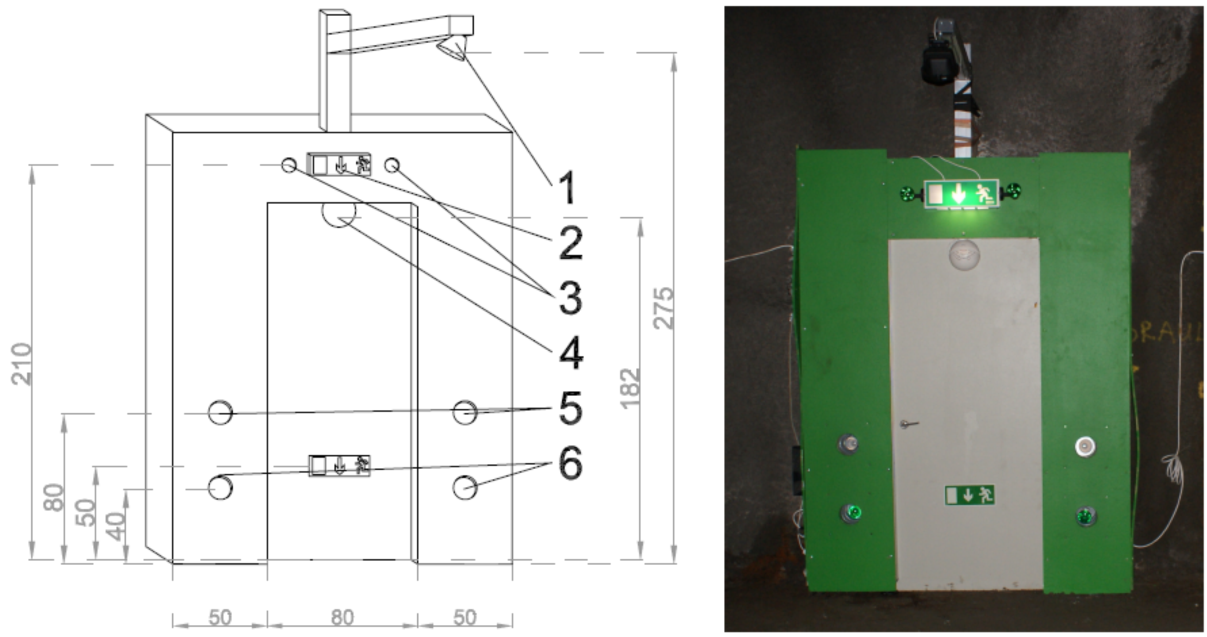


Figure 50: Way-finding setup around emergency exit [92] [93].

Way-finding Tool	Description
1. Halogen Lamp	500 W white halogen lamp installed above door direction light toward the exit providing 556 lux in normal conditions (no smoke).
2. Emergency exit sign	Standardised backlit exit sign in accordance with European standards.
3. Green flashing lights	Green flashing lights, consisting of two green lights bulbs, installed on each side of the emergency exit sign above door. Flashing occurred once a second at a frequency of roughly 1 Hz.
4. Loudspeaker	Installed on the upper centre part of the door to allow for an alarm signal and a pre-recorded voice message to be broadcasted.

	The voice message used a pre-recorded voice (a computer generated female voice) the repeated the saying (in Swedish): The sound is coming from an exit. Follow the sound in order to get out. The alarm used an increasing signal that was on repeat three times within 1.5 seconds and had a frequency range between 800 – 970 Hz.
5. Green lights	Green lights blubs were installed on each side of the door on the lower part of the frame providing a light source of 11 lux during normal conditions.
6. White lights	White light bulbs were installed on each side of the door on the lower part of the frame providing a light source of 63 lux during normal conditions.

Table 26: Description of the way-finding tool installed around emergency exit [92] [93].

To create the effect that the participants are evacuating from a real emergency the tunnel was filled with artificial smoke and acetic acid fumes to recreate as realistically as possible the conditions within a rail tunnel during a fire without putting the participants' health at risk. The smoke was used to reduce the visibility within the tunnel and consisted of a cold smoke that was produced by two smoke machines at the end of the tunnel. The smoke itself was a mixture of polyglycole and distilled water. The acetic acid was used to create the feel of breathing in smoke into the lungs and was spread through the tunnel by boiling the liquid at the beginning and end of the tunnel. A fan was used to distribute the acid and smoke inside the tunnel and was turned off when the participants were inside.

An ultra-violet camera was used by a fire fighter to film the participants as they conducted the experiment. The fire fighter, in full protective gear and wearing a breathing apparatus, would follow the participants through the tunnel and film their movements and behaviour. The fire fighter was also there as a safety precaution just in case any participant wanted to abort the experiment and leave the tunnel.

7.5.4 Experimental process

On the day of the experiments participants were asked to come in groups of 10 at a specific time of the day. However, only one participant at a time was inside the tunnel and the evacuation scenario was pre-determined by the activated way-finding tool around the emergency exit and the initial starting location inside the tunnel.

The experimental day was divided into three hour periods and at the beginning of the period the 10 participants were led into a parked bus, close to the tunnel, which served as the site office/meeting point for the experiment. The participants were welcomed and briefed about the experiment and the safety procedures. The information provided was a repetition of the information sent to the participants a couple of weeks prior to the experiment.

After the briefing one participant at a time took part in the experiments. Upon exiting the bus they were provided with safety equipment (overalls, boots, a helmet and gloves) and then led down to the tunnel entrance to watch a short film. The film was a first person view of a person travelling in a train in the Stockholm Metro which eventually came to a stop within the tunnel.

Once the film had ended the participant was led into the tunnel by a fire fighter who job, as stated before, was to film the evacuation attempt and assist the participant if he/she signalled for help. Once inside the tunnel the fire fighter led him/her to the first emergency sign of the tunnel. The side of the tunnel (left or right) was pre-determined by the research team and the participant was left on the appropriate side 203 meters in front of the sign and told to evacuate.

The end of the experiment occurred when the participant had either found the emergency exit or if they had walked past and found the end of the tunnel. The participants were then led out of the tunnel by a fire fighter and returned to the bus to fill out a questionnaire about the experiment. The participant was placed at the back of the bus so they could not interact with the others in order to prevent discussion about the environment, location of the exits, etc as such avoiding learning effects.

7.5.5 Experimental scenarios

As shown in Figure 50, there were a number of way-finding tools around the emergency exit that were used during the experiments. The participants could also either be positioned initially on the same side of the tunnel as the emergency exit or on the opposite side. Hence, combining the five different tools and the two initial positions of the participants inside the tunnel there is a possibility of a wide range of experimental scenarios. Over the three days of experiments two different way-finding tool set ups were used, hence, in total ten different scenarios were tested (See Figure 51 and Table 27).

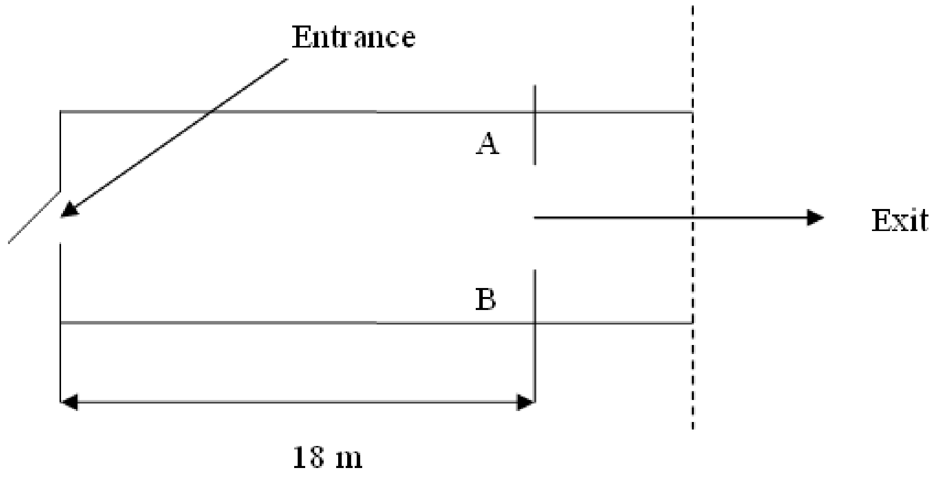


Figure 51: Possible starting location for participant.

Scenario	Way-finding Tool	Stating Position	Number of Participants
1	2	A	12
		B	12
2	2,3	A	10
		B	10
3	1,2,5,6	A	10
		B	16
4	2,4	A	10
		B	14
5	1,2,3,5,6	A	1
		B	5

Table 27: Number of occupants used for exit type of way-finding tool setup

7.5.6 Live evacuation data

The data collection process of the experiments was achieved using a thermal imaging camera (MSA Evolution 5600) used by the fire fighter who was in the tunnel at the same time as the participants. The participants were unable to see the fire fighter as the inside of the tunnel was dark and smoke-filled, obscuring vision. The videos were recorded onto a memory card and transferred onto a master hard drive after each evacuation to ensure no data was lost. The videos were used to analyse the movement speeds, walking strategies, exit choice and generally human behaviour of each participant.

In order to try and understand the decision-making process of the participants they were required to fill out a questionnaire, after the experiments. The questionnaire consisted of 26 questions that included both simple yes/no answers, multiple choice, scaled questions and open answer questions. The questionnaire included four sections that were general information about the participants, participants' behaviour during the experiment, way-finding tools and the perceived benefit of different tools, and how the participants felt during the experiment. The questionnaire was based upon the ideas suggest by Foddy [94] to ensure that the questions were not biased and reduce the possibility of misinterpretation.

After filling in the questionnaire, a few of the participants were also asked to take part in a one-on-one interview with a researcher. The interview involved sitting through the experimental video of the participants' evacuation and asking them to explain their behaviours and decision processes.

7.5.7 Experimental analysis

The analysis of the experiments was conducted by Karl Fridolf, from the University of Lund, Sweden, and published within the paper, "Movement speeds and exit choice in smoke-filled rail tunnels" [92] and discussed within the final report for the METRO Project [93]. Each video was systematically analysed in order to reconstruct the evacuation patterns of each participant, while also calculating the movement speed and documenting their exit choice. In order to calculate the movement speeds the analysis took into account the recording angle of the fire fighter filming each evacuation and the position of the participant in relation to the emergency signs on the tunnel wall. The position could be seen on the thermal imaging camera as there was heat radiation from the lights themselves. If the participant changed their direction of travel during the experiment the new position was estimated by counting the number of steps made and the distance between the participant and the tunnel wall.

The videos were also analysed to document the behaviours of each participant, including their way-finding behaviours, how they used the visual and tactile information provided, the positioning of their hands and their walking posture.

7.5.8 Participants' movement speed and egress paths

The video of each participant was analysed in order to determine the overall movement speeds and the egress paths based upon the scenario tested. The movement speed was calculated for each participant by dividing the total distance walked in the tunnel by the overall evacuation time.

The speeds were calculated based upon the section of the tunnel the participant used during their evacuation. Section A represented the first part of the tunnel, which consisted of a smooth floor material and a gradient of 10%, Section B consisted of the same smooth floor material with no gradient and Section C of the tunnel consisted of gravel and no gradient. However, the use of Section C was dependent on the initial starting position of the participants at the beginning of the evacuation and the walking route chosen.

Section	Number of Samples	Movement Speed (m/s)			
		Min	Max	Mean	Std
A	99	0.42	1.42	0.91	0.23
B	98	0.51	1.45	0.91	0.22
C	51	0.5	1.82	0.94	0.29

Table 28: Movement speeds of the participants [92]

As can be seen from the movement speed analysis it appeared that the 10% gradient and the uneven floor material did not have an effect on the overall movement speeds of the participants. This phenomenon went against the initial assumptions made by the research team. The results mean that it is possible that the defining factor in the movement speed of the participant is the level of lighting in tunnel and the amount of smoke present, not the gradient or floor material.

While analysing the movement speeds of the occupants the egress path was also determined. Initial assumptions, based on previous research, assumed that the participants would tend to follow closely along the wall they were initial positioned against. It was found that 91% of the participants demonstrated this behaviour by following one of the tunnel walls for at least 75% of the total distance walked during the evacuation. This behaviour normally occurs due to the fact the visibility within the tunnel is very limited and the wall is often used to orientate the participant inside the tunnel, with the assumption that the wall will eventually lead them to an exit out of the tunnel. The use of the emergency signs on the wall could have also influenced the participants to stay near the walls in a further attempt to orientate them towards an exit. During the interviews the research team found that a significant percentage of the participants found the emergency signs extremely important, hence, they were used by the participants as guidance points along the wall and a target to aim for while moving.

As stated above, to end the experiments the participant could either abort the run by asking for help from the fire fighter or by locating the emergency exit within the tunnel. If the occupants walked past the exit and towards the end of the tunnel the experiment was ended and the participant was led out of the tunnel by a fire fighter. Below is a summary of the scenario and the number of participants who managed to find the emergency exit.

Scenario	Initial Position	Number of Participants	Number of participants that used the emergency exit
1	A	12	12 (100%)
	B	12	8 (67%)
2	A	11	11 (100%)
	B	9	7 (78%)
3	A	8	5 (63%)
	B	18	12 (67%)
4	A	10	10 (100%)
	B	14	14 (100%)
5	A	1	1 (100%)
	B	4	4 (100%)

Table 29: Summary of the scenario and number of participants who found the emergency exit.

As shown in the table above the participants who were initially positioned on the side with the emergency exit (position A) had a higher probability of choosing the emergency exit compared to the participants walking on the opposite side. Hence, it could be concluded that the way-finding tools are significantly beneficial for people on the opposite side of the tunnel.

The standard emergency exit design, used in scenario 1, appeared to be not very effective at attracting the participants toward the exit from the opposite side. The addition of the flashing green light in scenario 2 increased the likelihood of the participant using the exit. The attraction of people towards flashing green lights was confirmed by studies conducted by Dr Daniel Nilsson where he concluded that flashing lights direct evacuee's attention and hence they will notice the exit more quickly [32].

The most effective way-finding tool proved to be the use of the audio message in scenario 4, with 100% of participants using the emergency exit. On analysing the egress paths of the participants in scenario 4 it was apparent that the occupants on the opposite side of the emergency exit started to move towards the other side of the tunnel more quickly and in a shorter distance than in other scenarios. Scenario 5 also had a success rating of 100% of participants using the emergency exit, which used every way-finding tool except the loud speaker. Unfortunately, due to the low number of participants in the scenario the data is not conclusive and should possibly be discounted. The poorest performing way-finding tools, used in scenario 3, was the combination of the emergency exit sign, the halogen spot light and both the white and green lights. From the video analysis it appeared that set up deterred participants from using the exit rather than attracting them. It was later found in the interviews that the participant who did not use the exit initially thought the door was a stationary train inside the tunnel. Hence, this uncertainty led the participants to stay with their already chosen walking paths and head past the door, towards the end of the tunnel.

The more common egress paths for the participant are shown below based upon their initial starting positions (Scenario 2 and 4 respectively).

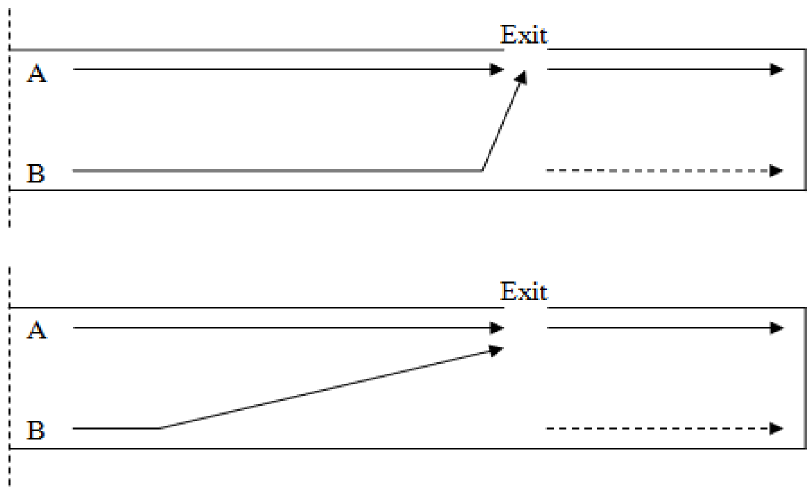


Figure 52: Common egress paths for the participants.

7.5.9 Discussion & Conclusion

The experiments conducted provide data on the effectiveness of a wide range of way-finding installations while highlighting the importance of providing information to occupants and how the design of an exit may influence the decision-making process. Furthermore, the study demonstrated how the installations could influence the movement speed and patterns of movement of the occupants who find themselves in an unknown situation and environment. It may be argued that the results cannot be applied for every possible egress situation that could occur in a tunnel, as no two fire scenarios are similar. However, within an underground tunnel the presence of smoke can be detrimental during the evacuation process and is often associated as the worst case fire scenario.

The analysis showed that the movement speeds produced during the experiments are similar to those presented in previous studies conducted. However, the data suggest that the movement speed is not influenced by the type of floor material used or the presence of a gradient. Hence, the presence of smoke and the lack of lighting seem to be the defining factors that affect the speed of the occupants during an evacuation of a tunnel. Other factors could include the effects of fatigue caused either by the long distance the occupants have to walk (~180m) and or by the stress felt due to being placed within an unknown environment/situation. However, stress may not occur for the entire evacuation as the occupants may start to become familiar with the environment/conditions reducing the feeling of anxiety and fear.

The dominant behaviour present throughout the experiments was the use of the tunnel walls by the occupants to help them navigate through the smoke-filled environment. The videos analysis showed that 91% of the participants followed one of the walls at least 75% of the total distance during the evacuation. The tunnel walls were used to facilitate the occupant's orientation inside the darkened smoke-filled environment and often an occupant would place one or two hands on the wall in order to remain in contact with it. In addition, along both walls emergency signs/lighting were installed every 8 metres. The signs provided the only light source and information on the distance and direction of the emergency exits and hence staying near the signs was desirable option. The information provided participants on the distance they had to walk in the tunnel and helped confirm that they were traveling in the correct direction, further reducing the stress they may have felt during the experiment.

The main purpose of the experiment was to analyse the effect of different emergency exit design and way-finding installation based upon its ability to attract the participants. The participants who walked along the side of the tunnel with the emergency exit used it to a greater extent than those who walked on the opposite side. Hence, the type of way-finding installation around the emergency exit will be significantly more beneficial for the participants who are evacuating along the opposite side of the tunnel from the exit. Of the installations tested, the door equipped with the loudspeaker, which broadcasted an alarm signal and a voice message, was found to be the most effective at attracting the participants to the exit. The least effective was the combination of a continuous green and white light source with a strong halogen lamp. This installation was misinterpreted by many of the participants as a train even though the lights were visible through the dense smoke, it led to the participant avoiding using the exit due to the uncertainty associated with it.

The experiments tested how the different installations would work within a tunnel environment, yet it is unknown how they would work within another location, for example a building. Within a building the use of a continuous light source may have a higher success rate than shown within the tunnel experiments. A continuous light may be received more openly as an installation within a stairwell or office floor as the occupants may use the lights as an orientation tool to guide themselves towards safety. On the other hand, the most efficient installation within the tunnel, the loud speaker, may be less effective within a confined location. This may be due to the fact that there will be a large number of walking routes and exits compared to a tunnel, meaning that there would be more than one speaker used on a floor at one time. This will increase the chance of possible cross audio contamination between the speakers, reducing their effect on guiding occupants towards the exits. Within the tunnel there was only one speaker and hence it was effective at gaining the attention of the participants as there was only one audio source to focus upon.

The experiments stressed the importance of using way-finding tools around an emergency exit and the effects each design had. The use of smoke during the experiment showed that certain set ups of way-finding may be confusing for participants, e.g. continuous lights, while showing other tools could reduce the confusion, e.g. flashing green lights. The use of a loudspeaker near the emergency exit was found to be highly effective at attracting a participant to use the door, irrespective of the side of the tunnel they were walking on.

7.6 Experimental Series 3 - Office floor evacuation with various way-finding tools

The final experiment conducted took the information gathered from the first two experiments on the effects and ability of occupants to learn and how they interacted within the way-finding tools. Its purpose was to determine whether it was possible or not to influence an occupant's exit choice, using way-finding tools, when the preferred route is unusable.

The relevant experiments consisted of two separate evacuation tests which were conducted at the University Of Edinburgh, Scotland, in 2011. The first experiment was conducted to calculate the flow rates and reaction time of occupants during a "normal" evacuation. The occupant's exit choices and behaviours were to be analysed. In the second experiment it was intended to analyse the same information as the first, however, the main stairwell would be rendered "unusable" to the occupants. The main objective of the second experiment was to see whether or not an occupant's exit choice can be influenced by the use of a combined visual and audio way-finding system.

The following is the breakdown of the experiment and the analysis of the results gathered.

7.6.1 Large-scale location

The large-scale experiments were held on the 3rd floor of the Alexander Graham Bell (AGB) and William Rankine (WR) Buildings at the University of Edinburgh. These buildings were chosen based upon the emergency exit design, as there are a number of different possible exits on the 3rd floor that can be used during an evacuation. It should be noted that the experiments were confined to the investigation of the effect on the horizontal movements of the occupants, not their vertical movements in the stairwells.

In order to capture the live data from the experiments, five video cameras were installed throughout the floor. Each of the five cameras were used to record different parts of the building to gather information on the number of occupants within the building, their behaviour, reaction time, flow rates and exit choice. In order to validate the information gathered from the cameras during the second experiment, the occupants were asked to complete a questionnaire that focused on their perception and interaction with the way-finding tools used.

7.6.2 Test participants

The experiments were carried out on two separate dates: 25th January and 1st May 2012. The occupants consisted of academics, postgraduate students, researchers, undergraduate students and visitors. The goal was to have at least 30 to 50 occupants present in each experiment. Some of the occupants who took part in the experiments were present for both the experiment of the 25^{th} of January and the 1^{st} of May.

7.6.3 Test scenarios and equipment

In order to identify the percentage of occupants who chose the main exits over the emergency exits, a "normal conditions" evacuation experiment utilising the standard alarms installed in the buildings was carried out.

Following this experiment, another experiment was to be conducted to study the influence of way-finding tools on the evacuation process and exit choice of the evacuees. This would be done by closing off the main exit in the centre of the two buildings to recreate the effects of a smoke-filled stairwell and testing both visual (LED lights) and audio (speakers) way-finding systems.

Therefore the experiment is divided into two parts:

1.	Normal evacuation conditions with standard alarms
2.	Evacuation with main stairs "smoke filled" with "way-finding" tools (directional audio and LED lights)

Table 30: List of experiments conducted

In the second test, the stair was to be "blocked" off by having two people stand at the main doors to the stairs and warning occupants that the stairs are unusable and advising them to find another exit out of the building. As the experiment would only be using the 3rd floor of the building, artificial smoke was not used for the test, see Figure 53 for the experimental summary.

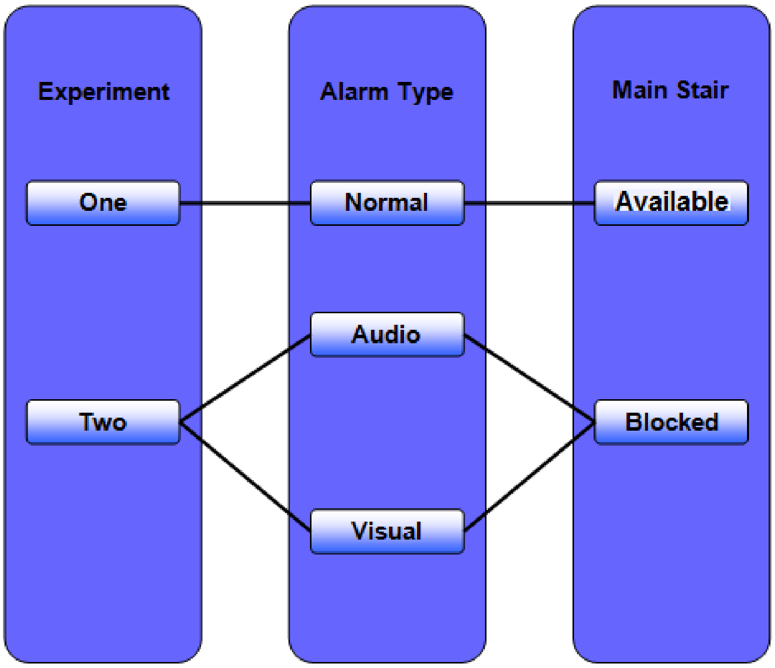


Figure 53: The set up for each experiment

The locations for the cameras used to capture the experiments can be found in Figure 54. The purpose of each camera and the information it gathered is given below in Table 31.

Camera:	Purpose:
1.	For measuring the number of evacuees using the exit. Placement: On the pillar within the William Rankine office 3.43 facing down the corridor.
2.	For measuring the flow rate, density and starting location of the evacuees. Placement: Above the door connecting the two buildings facing towards the coffee area.
3.	For measuring flow rates, density, starting location and exit choice. Placement: Above the door within the corridor connecting the two buildings facing towards the main stairwell.
4.	For measuring flow rates, density, starting location and exit choice. Placement: Above the door within the main corridor within the Alexander Graham Bell Building facing towards the main stairwell.
5.	For measuring the number of evacuees using the exit. Placement: Above the office

	3.12 door facing towards the secondary exit from the Alexander Graham Bell Building.

Table 31: Purpose and location of the cameras

Figure 54: Location of cameras used during experiment (Cam 2 and Cam 3 are located on different sides of the same door).

The purpose of the tools used in the second evacuation experiment was to see if it was possible to exploit them to deter occupants from using an exit that has become unavailable, either due to smoke or fire, and to attract occupants towards an exit that is safer to use during the evacuation.

The audio equipment was Altec Lansing Orbit M Portable 3.5mm Speakers, mounted in two separate locations (Figure 55 and Figure 56). The speakers located above the main exit within corridor 2 were used to attempt to deter occupants away from the main stairwell. The speaker played the following message, which repeated every 3 seconds until the end of the experiment:

> "This stairwell is blocked, please find another exit"

In contrast, the other speaker located within corridor 1 was used to attempt to attract occupants towards the secondary exit with the AGB building. The speaker played the following message, which also repeated every 3 seconds until the end of the experiment.

> "Exit available, please exit this way"

As discussed within Section 5.3.1, occupants are more likely to listen to and follow an audio message that appears to be given by a human rather than a machine [59]. Hence, the audio message used for the experiments was the pre-recorded message that used a voice actor who had a voice that would be familiar to the majority of the occupants. The actor attempted to create the feel that the message was being broadcasted live by including blemishes of a human touch i.e. stuttering and pauses.

Figure 55: Location of speakers a) AGB corridor, b) foyer entrance (see Figure 56)

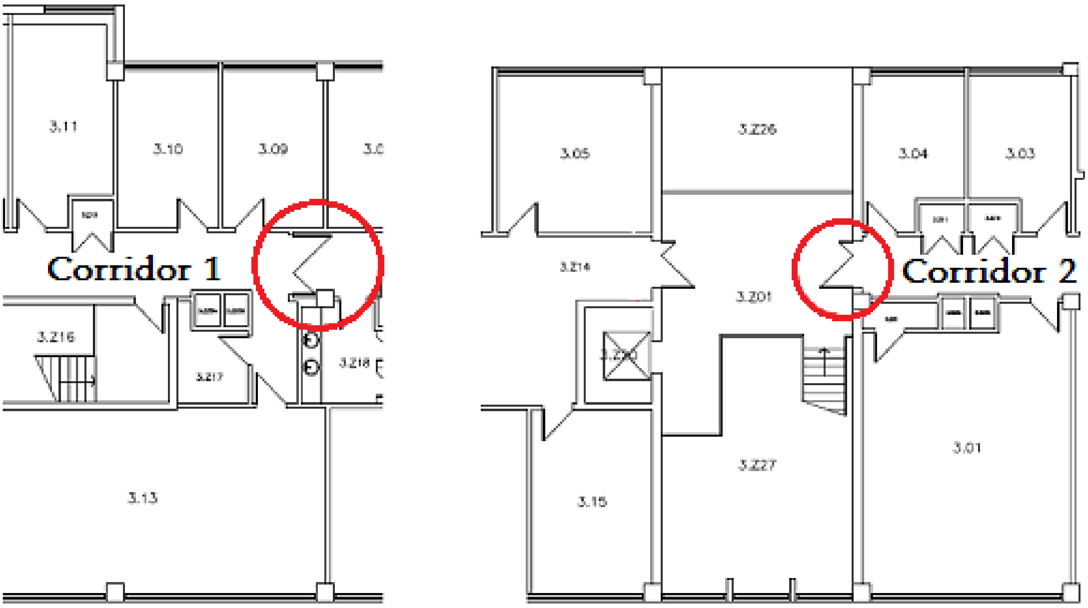


Figure 56: Installation location for speakers

The visual equipment used consisted of four battery-powered strips of eight red LEDs and three battery-powered strips of eight green LEDs that were mounted on two separate doors (see Figure 57 and Figure 58). The red LEDs located on the main exit within corridor 1 were used to attempt to deter occupants away from the main stairwell. This approached differed from the directional audio message as no information was provided to the occupants other than the colour red. The lights were tested to see if the colour red on an exit would deter the occupants to use a specific exit and engage in searching for an alternative route/exit. As with the directional audio equipment the purpose of the green LED lights was to attempt to attract occupants towards an underutilised secondary emergency exit. The lights were installed upon the secondary exit within corridor 2 directly across the corridor from the seminar room (room 3.02 on Figure 54).

Figure 57: Location of LEDs a) foyer entrance, b) Seminar room corridor

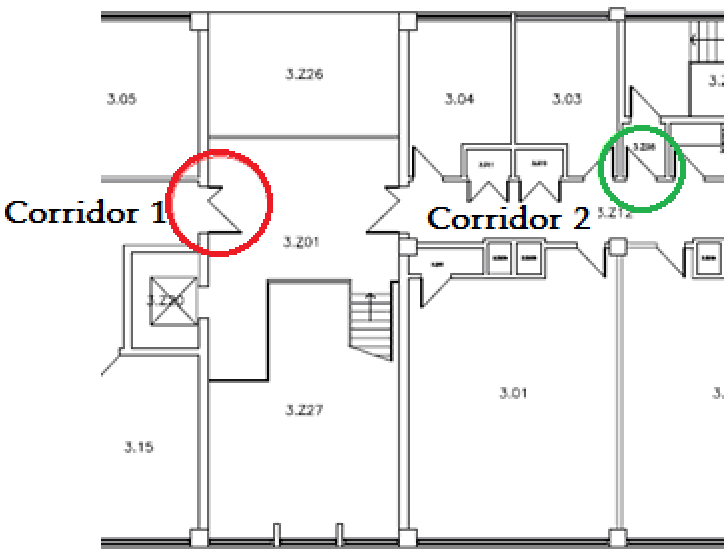


Figure 58: Installation location for green and red LEDs

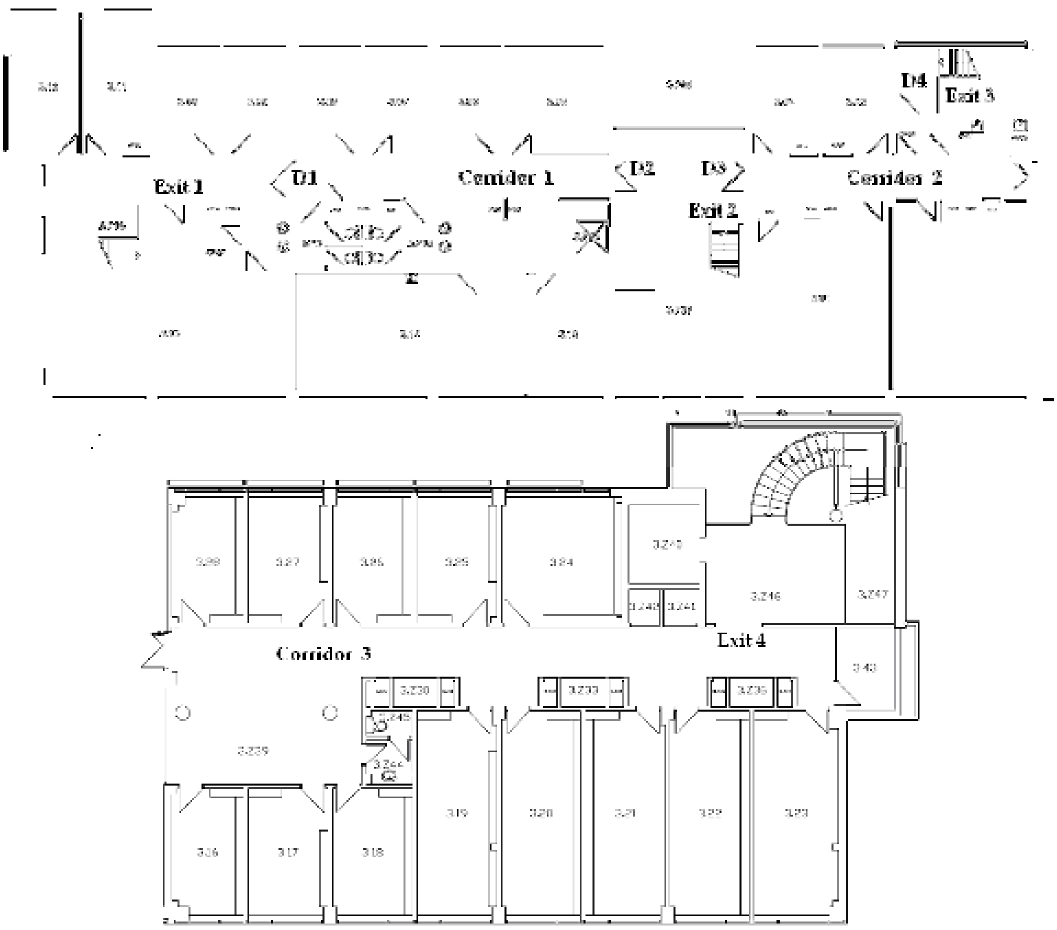


Figure 59: Location of exit within the building

7.6.4 Exit location

There are four possible exits an occupant could have used during an evacuation to egress from the building to a safe location, immediately outside the building. The four exits are displayed above in Figure 59. It should be noted that the majority of the occupants where only familiar with Exit2 and Exit 4. Exit 1 is located at the far end of the AGB building and is defined as the secondary exit which means that is not intended to normally be used for everyday access to the building. Exit 2 is located within the main stairwell (central foyer) and is the most commonly used exit as it can be accessed from both buildings. It is referred to as the main exit/entrance for the building. Exit 3 is located within the corridor opposite the main seminar room for the buildings; it is considered the secondary exit for the WR building though it is not routinely used as an exit. The final exit is located within the WR building and is the commonly used by the occupants of the immediate area as the main exit from the building.

7.6.5 Experimental procedure

As stated above, the experiments were undertaken on different days. Hence, the number of occupants was dependent on who happened to be within the building at the time of the alarm. The experiments were to be conducted on a day where the seminar room was being used in order to increase the occupancy load upon the floor. The night before the experiment the cameras and the appropriate way-finding tools were installed within the building. Approximately 5 minutes before the alarm was activated the cameras and the equipment were turned on. The experiment was concluded once the entire floor was evacuated and the alarms had been turned off by the fire warden.

7.6.6 Analysis of the live evacuation experiments

As stated before in section 7.2.2 the purpose of the evacuation experiments was to study the behaviour of the occupants during a "normal evacuation" and during an evacuation where the main exit route was unavailable for use. The experiments also looked into the behaviours that affect the decision-making process that occurred when both new visual and audio way-finding tools were introduced during the evacuation. The following section will address each experiment as a separate analysis before comparing all the results within the discussion and conclusion of this chapter.

7.6.7 Evacuation Trial 1 – normal conditions with standard alarms

The first trial was conducted on Wednesday the 25th of January 2012. The alarms are tested every Wednesday at 2:00pm by the delegated fire safety officers to ensure the system is in full working order, by activating the alarms for 10 seconds. On the day of the experiment it was agreed to change the testing time to 1:39pm and for the alarm to continue until the fire warden had advised the fire department that the level was evacuated before deactivating the system. The test condition for the experiment used the standard alarms installed within the building with all four exits available to be used. These conditions are referred to as the "normal evacuation conditions" and rely on the standard sounders within the building to initiate the evacuation only.

In order to achieve an occupant sample size large enough for the experiment without telling the participants that they were to take part in an evacuation a meeting was planned by the fire engineering group within the shared seminar room. Out of the 49 occupants only four people were aware of the evacuation, which included two fire wardens, the organiser of the meeting and the PhD researcher who was conducting the experiment. The remainder of the occupants were staff members, PhD students, visiting researchers and an electrician.

The results from the experiments were calculated using the floor plans of the level and the videos recorded by the camera and are displayed below in Table 32 and Table 33. The reaction time is defined as the time taken for an occupant to begin their evacuation (after they become aware of the evacuation i.e. sounding of the alarm and the movement of people) and the waiting time is defined as the time taken from the alarm sounding till the occupant became aware of the evacuation (normally after being warned by a warden).

Results:	Average Time (sec)
Total evacuation time	165
Waiting time	65
Reaction time	82

Table 32: Live results for evacuation, waiting and reaction time

Results:	Average Walking Speed (m/s):
Occupants	1.20
Wardens	1.34

Table 33: Live results for walking speeds

7.6.8 Human behaviour trial one

The video cameras stationed throughout the 3rd floor of the building were able to record the behaviours of the occupants that took part in the experiments. The main objective of the first trial was to analyse the exit choice of the occupants based upon their starting locations. Table 34 shows that the most commonly used exit from the building was Exit 2, followed by Exit 4. This behaviour was expected as Exit 2 is the common entrance used by occupants as the main entrance to the building, therefore becoming the most familiar exit to be used during an evacuation as the occupants have confidence that it will exit to safety. Exit 1 and Exit 3 were not fully utilised during the evacuation as the majority of the occupants were unaware of the exit locations as they are not regularly used; however, Exit 3 was used by three students during the evacuation. The first student to use the exit had used it before and headed directly towards it from the seminar room. On seeing a participate use the door, two other students directly followed through the same exit. After the third student went through the door there was a gap in the flow from the seminar room, consequently the next student did not witness the use of the door, and the flow of people continued towards Exit 2. The phenomenon of occupants following others towards an exit occurred throughout the experiment. One of the fire wardens heading towards Exit 4 near the end of the experiment potentially influenced four students who were behind him in the corridor to head towards the Exit 4 as well.

Exit Choice	Number of Occupants
Exit 1	0
Exit 2	37

Exit 3	3
Exit 4	9

Table 34: Exit choices of occupants

The movement paths of the occupants varied greatly during the evacuation and were apparently influenced by the starting location of each occupant and the interactions that occurred with other occupants within the corridors. The figures below demonstrate the most common movement paths that occurred during the evacuation. Figure 60 shows the occupants who used the Exit 2 and their starting location. It can be clearly seen that occupants headed directly to the main stairs, ignoring the exits which were closer to their starting location.

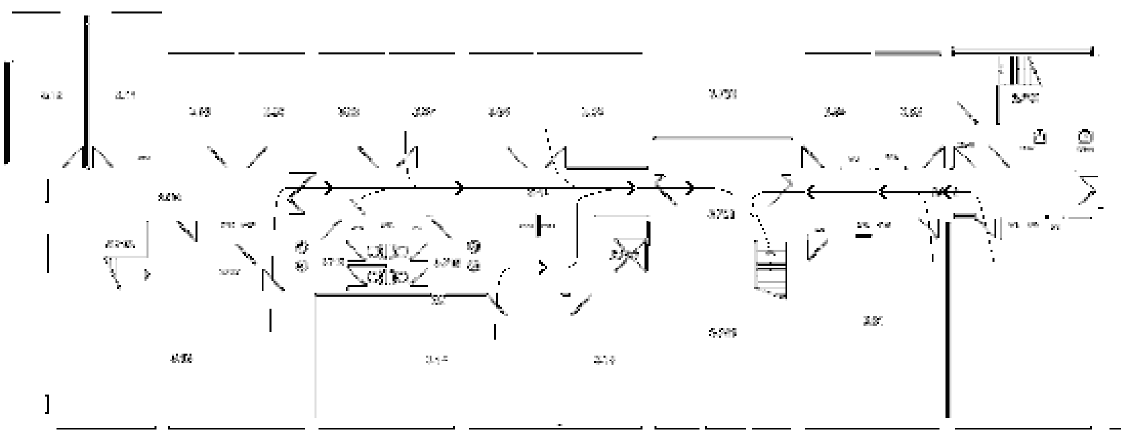


Figure 60: Movement path of occupants who used Exit 2

Figure 61 shows the movement paths of the occupants who were in the seminar room who did not use the main exit to evacuate from the building. It can be seen the majority of the occupants headed towards Exit 4 and ignored the exit directly across from the seminar room (Exit 3). However, even though Exit 3 is the quickest possible route out of the building from the seminar room, the exit signage above the door is often missed by occupants as they evacuate, hence, Exit 3 was used only by three occupants.

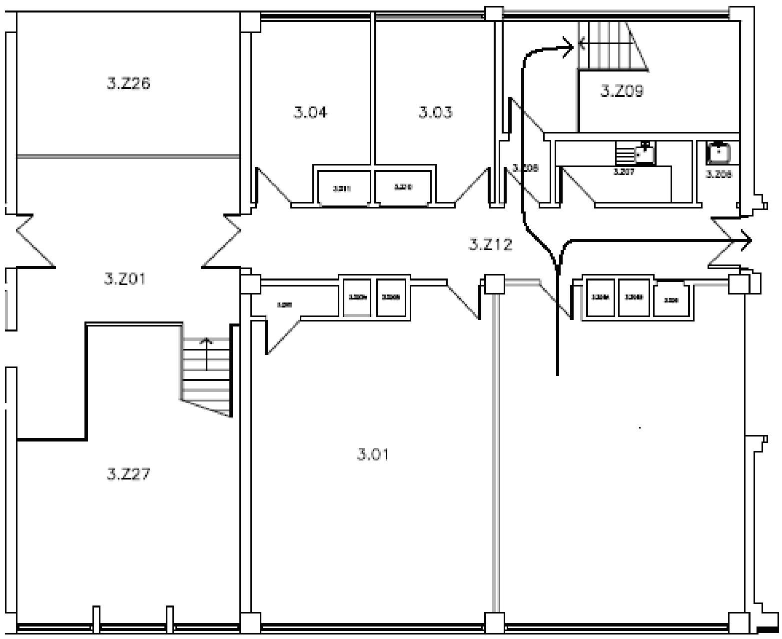


Figure 61: Movement path of occupant's part 2

The remainder of the movement paths, Figure 62, shows the continuation of the movement path of the occupants from the seminar room as they continue towards Exit 4 as well as the other occupants who used Exit 4.

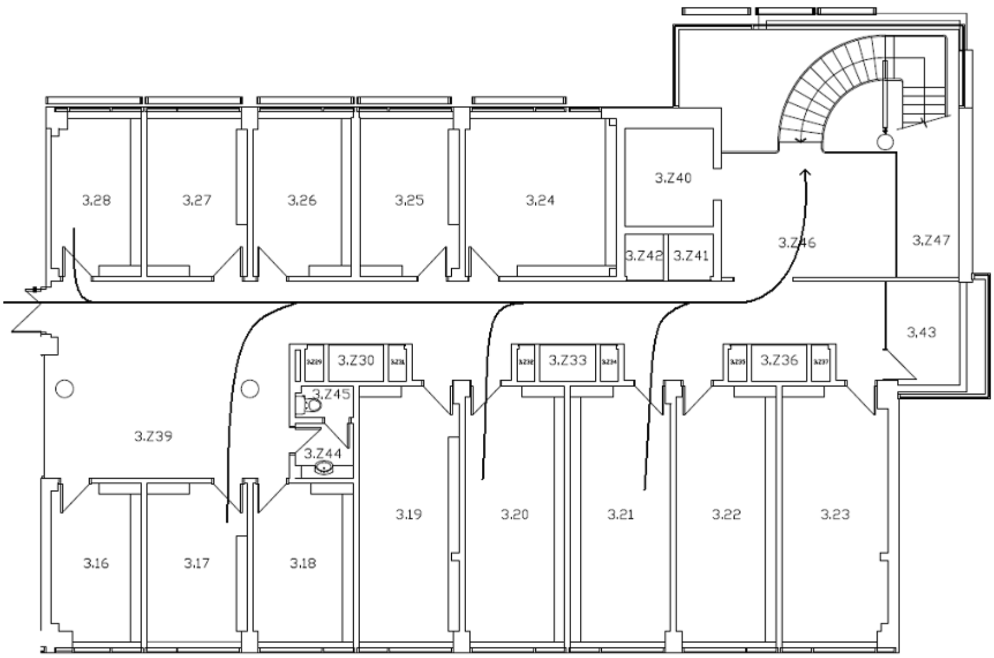


Figure 62: Movement path of occupant's part 3

The occupants within rooms 3.17, 3.28, 3.20, and 3.21 were all told by the warden to exit before they reacted to the alarm. Initially, at the beginning of the experiment only two occupants were meant to behave as fire wardens. However, during the evacuation three extra occupants demonstrated warden like behaviour and starting checking the offices to ensure everyone had evacuated.

When the alarm was activated only one of the 43 occupants, who was not displaying fire warden behaviours, began to evacuate the building without being advised to by a warden. Therefore, the occupants waited for a long time before reacting to the fire alarm, which meant that if a real fire had occurred, these occupants may not have enough time available to leave the affected area as the conditions could have become hazardous or even deadly.

An undesirable behaviour captured on video was once the occupants were warned to evacuate they still waited on average 50 seconds before evacuating the building. During this time, occupants were seen on their computers, putting away items, gathering jackets and locking their office doors. This "extra" time needed for these behaviours could potentially put the occupants at risk in a real fire.

The most common behaviour displayed by a majority of the occupants was the gathering of jackets before entering the corridor to begin to evacuate. Three occupants who were in the seminar room as the alarms activated took this requirement for a jacket to the extreme and as they headed straight to their offices to get their coats they walked past two exits and pushed their way through people evacuating from the other half of the building.

The majority of the occupants appeared to be calm and unstressed during the evacuation, with some occupants making jokes and smiling as they exited the building. Therefore, it can be concluded that after an initial moment of confusion occupants became aware that the alarm was for a practice evacuation and not for an emergency. This could have been due to the fact that no visual stimuli were present during the evacuation and also that the alarm was set off on a Wednesday close to the time that the alarms are tested every week. Therefore, it was apparent that the second trial would have to be conducted on a different day to ensure this behaviour did not occur again.

7.6.9 Evacuation trial two – main stair unavailable and new way-finding tools

The second trial was conducted 98 days later than the first on Tuesday the 1st of May 2012. In order to try and combat the behaviours experienced during the first trial the alarms were not set off on the normal day of testing nor at the normal testing time. This was to create uncertainty within the occupants with the aim of simulating a more "realistic" evacuation scenario.

The purpose of this trial was to investigate the effect on the flow rates of the occupants due to the main exit being unavailable for egress purposes, while studying their behaviours and decision making. In addition, new visual and audio way-finding tools were installed within the floor to determine whether or not the exit choice of the occupants could be influenced based on the type of tool used and the information the tool provided.

On the day of the experiment the alarm was activated at 1:21pm and continued until the fire warden had advised the fire department that the level was evacuated before deactivating the system. However, as the main stair was unavailable for use, the single warden was only able to warn occupants on one side of the building. This allowed for the study of the behaviour of occupants who were warned to evacuate compared to those who were not.

As with the first experiment, a meeting was held by the fire engineering group to ensure large number of occupants were present during the evacuation. The meeting on the day was an annual event where the graduating Masters students were to present their thesis work to the fire group. Out of the 42 occupants only two people were aware of the evacuation, which included one fire warden (the other was away on the day of the experiment) who also was the organiser of the meeting, and the PhD researcher who was conducting the experiment. The remainder of the occupants included staff members, PhD students, master's students, visiting researchers and an undergraduate student. It should be noted that 63% of the occupants from the first experiment formed part of the second experimental group.

The results from the experiments were calculated using the floor plans of the level and the videos recorded by the camera and are displayed in the tables below (for details of the analysis see Appendix A). The results are provided for each building based upon which side of the closed exit the occupants were on. Hence, WR results refer to the occupants who were in the WR building and the corridor that contains the shared seminar room, while AGB refers to only the occupants who were within this building and not the seminar room.

Results AGB:	Average Time (sec)
Total evacuation time	126
Waiting time	53
Reaction time	53

Table 35: Live results for AGB evacuation, waiting and reaction time

Results WK:	Average Time (sec)
Total evacuation time	138
Waiting time	32.2
Reaction time	39.5

Table 36: Live results for WR evacuation, waiting and reaction time

Results AGB :	Average Walking Speed (m/s):
Occupants	0.93
Wardens	N/A

Table 37: Live results for AGB walking speeds

Results WK:	Average Walking Speed (m/s):
Occupants	1.08
Wardens	1.25

Table 38: Live results for WR walking speeds

7.6.10 Human behaviour trial two

As with the first trial, the video cameras stationed throughout the 3rd floor of the building were able to record the behaviours of the occupants that took part in the trials. However, the main objective of the second trial was different than that of the first. The objective of the second experiment was to analyse the initial exit choice of the occupants and to investigate if the use of either visual or audio way-finding tools could influence the exit choice based on the type of information provided.

The table below shows the final exit choices of the occupants during the experiment

Exit Choice	Number of Occupants
Exit 1	11
Exit 2	0
Exit 3	21
Exit 4	10

Table 39: Exit choice of occupants

The most common exit from the AGB building was Exit 1 (end stair, see Figure 59), which was expected as it was the only other possible exit from that building once the main stairs had become “inaccessible”. However, 4 out of the 11 occupants who used Exit 1 tried to exit the building via the main stairwell (Exit 2) before being told the stairs were unavailable. As these occupants walked towards Exit 1 they can be seen on the video advising other occupants in the corridor that the main stairwell is blocked and they must find another way out of the building. Within the corridor of AGB the following way-finding tool setup was installed, see Table 40:

Type of tool	Location	Description
Visual	Corridor leading to main stairwell	4 strips of Red LEDs (8 Bulbs) Two installed upon the door Two installed above the door frame
Audio	Internal fire door within corridor 1	Audio speaker above the door frame repeating: “Exit available, please exit this way”

Table 40: Way-finding tools installed within AGB

During the experiment it was observed that two of the occupants start to head to towards the main stair via the fire doors within the corridor (where the speaker was located), stop, turn around and appear to be listening to the information provided by the speaker before heading back through the door and towards Exit 1. Another occupant was observed heading towards the main stairwell from room 3.14 and stopping mid-way down the corridor before turning around and heading towards the other exit. From his location on the camera it would be impossible for him to have heard the audio message, leaving the only conclusion being that he saw the red LEDs and deduced that the main stair was unavailable.

The use of Exits 3 and 4 within the WR building were dependent on the starting location of the occupant at the beginning of the experiment. Exit 3 went from being the least used exit during experiment one to the most common with the

WR building. Of the 24 occupants located near Exit 3 initially, only three attempted to evacuate the building via the main stairwell. Two of the occupants were turned back and the third ignored the research team and walked through the exit to his office with the AGB building. Within the corridor of the WR building the following way-finding tools were installed in front of the seminar room:

Type of tool	Location	Description
Visual	Corridor leading to main stairwell	3 strips of Red LEDs (8 Bulbs) Installed upon the secondary exit door
Audio	Above door leading to main stairwell	Audio speaker above the door frame repeating: "This stairwell is blocked, please find another exit"

Table 41: Way-finding tools installed within WR

It would appear that the increased favourability of Exit 3 can be explained by two factors that occurred during the experiment. The initial factor is that one of the occupants would see the green LEDs upon the exit door straight across from the seminar rooms exit and evacuate via this exit. Once the first person used the door the occupant directly behind them would follow through the exit and this would continue until a gap occurred in the flow that was long enough to allow the door of the emergency exit to close. Then the process would repeat again, initially an occupant would see the lights, head through the door and other occupants would follow. This behaviour is common during an evacuation [95] and occurs because a proportion of the occupants will look towards other occupants who appear to be confident and assertive to flow towards an exit as it appears that they will know a safe route out of the building.

The occupants within the main WR building all used Exit 4 to evacuate from the building. This was expected, as the exit was still available during the experiment and no way-finding tools were installed near the exit. In fact, an occupant who was having a meeting within an office near Exit 4 walked towards his office, which is located across the corridor from Exit 2, to grab his jacket before returning to Exit 4 to evacuate. The occupant can be seen on the camera noticing the green LEDs while he walks past the exit towards Exit 4.

The movement paths of the occupants varied greatly during the evacuation and were influenced by the starting location of each occupant, the type of way-finding tools installed and the interactions that occurred with other occupants within the corridors. The figures below demonstrate the more common movement paths that occurred during the evacuation. Figure 64 shows the occupants who used the Exit 1 and their starting location. It can be clearly seen that the majority of the occupants first head towards their normal exit from the building (Exit 1) before either being turned back as they have been informed of the smoke by the researcher or after discussing with fellow occupants about the unavailability of the main stairwell.

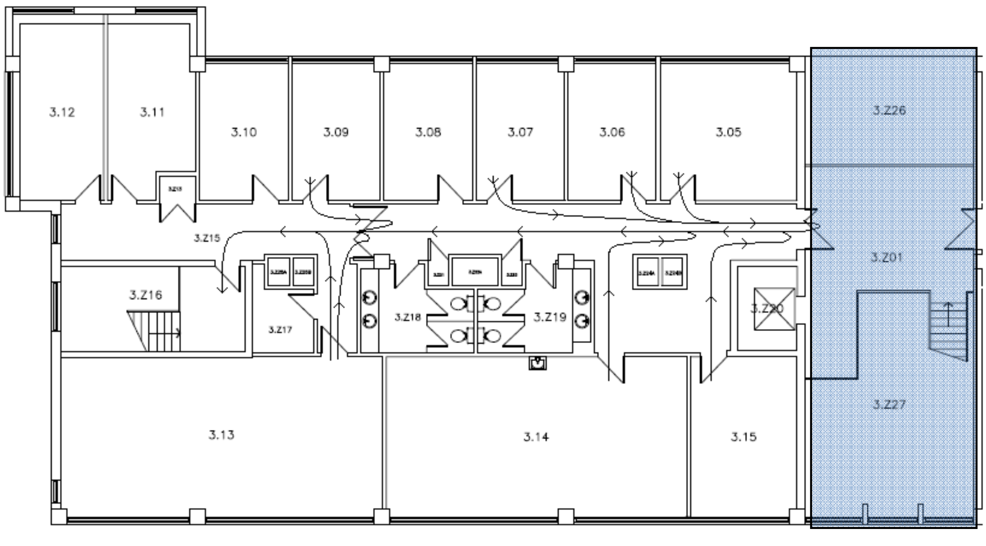


Figure 63: Movement paths of the occupants within AGB

Figure 64 shows the movement paths of the occupants who were in the seminar room or the corresponding corridor at the beginning of the experiment. It can be seen that the occupants who were located in rooms across from the secondary emergency exit used this exit, unlike the first experiment where only three occupants used the exit. The exit sign location for the secondary exit is not ideal for occupants within the corridor or those within the seminar room as unless they are looking for an exit it can be easily missed under evacuation conditions. It might be plausible that the LEDs helped attract the occupant's eyes towards the door, making the exit sign easier to detect.

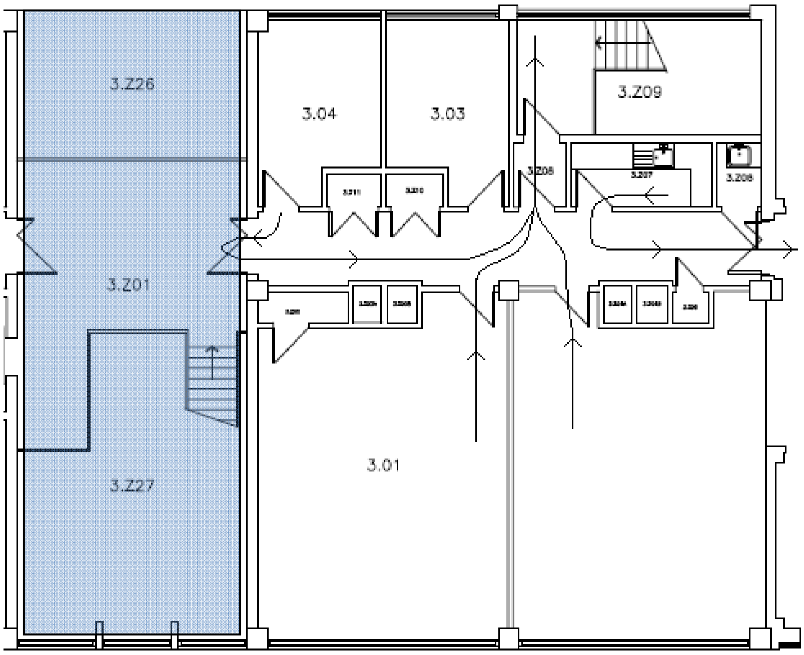


Figure 64: Movement paths of the occupant's part 2

The final movement path, Figure 65, shows the movement path of the occupants who were located within the main sector of the WR building at the time of evacuation. All occupants within this section chose to use Exit 4 even though for half of the occupants Exit 3 was closer or of similar distance. This is because these occupants would normally use Exit 4 to enter/exit the building during working hours.

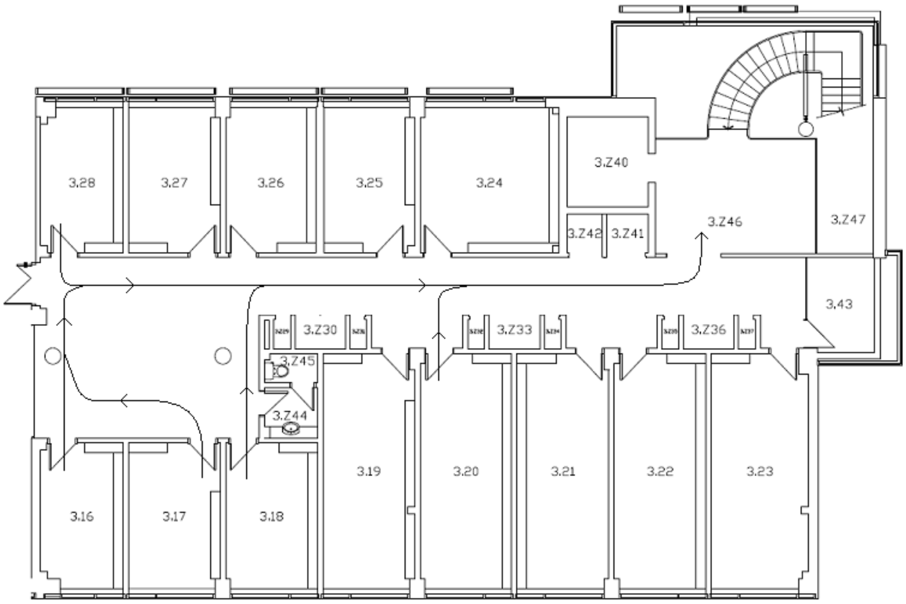


Figure 65: Movement paths of the occupant's part 3

When the alarm was activated only two of the 40 occupants, who were not displaying fire warden behaviours, had to be warned and asked to leave by a fire warden. Therefore, the waiting time of the occupants before reacting to the fire alarm was significantly reduced compared to the time observed in the first trial. The number of occupants who gathered jackets before leaving the building also reduced significantly from the first trial.

The demeanour of the occupants appeared to be different during the second trial compared to the first. In the first trial the occupants appeared to be calm and unstressed during the evacuation, however, during the second trial some of the occupants appeared to be confused yet focused during the processing of the information provided before evacuating, which was seen via the increase of investigatory behaviour and from the results of the questionnaire discussed later within the chapter. It was concluded that due to the fact the alarms were activated on a Tuesday and not the normal testing day (Wednesday) most occupants believed a real emergency had occurred and the urgency to evacuate had increased. A possible significant cause of confusion experienced by the occupants was the unavailability of the most commonly used exit, Exit 2, and the addition of new way-finding tools that had not been used before. This was expected and it had been assumed that the way-finding tools may be confusing for some of the occupants, but not to all.

In order to determine if the behaviours of the occupants derived from the video analysis were justifiable a questionnaire was distributed after the second trial to find out how the occupants managed the information provided by the way-finding tools and a basic look at the thought process during the evacuation, as discussed in the following section.

7.6.11 Results derived from trial two questionnaire

The questionnaire provided to the occupants was divided into three sections in order to gather information based on the type of way-finding tools they encountered during the evacuation, following the philosophy derived by Foddy [94] and is provided with Appendix A.

The first section asked the occupants about their gender, age and occupation. The next section covered the occupant's initial starting location and reactions/thoughts when the alarm was activated. The final section was broken into two parts and had varying questions depending on which side of the main stairwell the occupants where during the evacuation (questionnaire is available within Appendix).

Below, in Table 42, information on the gender, age and profession of the occupants who completed the questionnaire is provided. Out of the 42 occupants who took part in the experiment 24 completed the questionnaire.

Information				
Sex		Male	Female	
		17	7	
Age	18-24	25-34	35-44	45+
	4	13	5	2
Profession	PhD	Researcher	Professor	Other
	8	7	4	5

Table 42: Questionnaire general information

The majority of the 24 occupants were located within the seminar room at the beginning of the evacuation. The remaining occupants were spread throughout the third floor on both sides of the main stairs.

When the alarm was activated the most common initial reaction was to check to see if it was a test as the alarms are normally activated every Wednesday and the experiment was held on a Tuesday. Even though 75% of the occupants initially believed the alarms were being tested they began to evacuate without waiting to be told by a fire warden, unlike the first experiment where over 95% had to be told to evacuate. The key factor in the occupants beginning their evacuation without being warned was the change in the normal alarm testing procedure, i.e. a change of day and activation time. This initiated a sense of uncertainty within the occupants, which led them to think that it may be a real emergency.

The majority of the occupants, according to the questionnaire, used the exit they headed for first, which was not the main stairwell but instead one of the secondary exits. These occupants stated that their exit choice was based upon the information provided to them by the other occupants and the way-finding tools.

The majority of occupants located within the seminar room stated that they used the secondary exit because their eyes caught sight of the green LEDs and then the exit sign. On the other side of the building occupants stated they saw the red lights but were unsure what they meant and instead listened to the audio message playing within the corridor.

The occupants within the experiment were unaware of the new way-finding tools being tested and had no previous training in what they actually meant. Most occupants found the lights to be “odd” yet decided the lights and audio message meant that it was an alarm failure and it was either an emergency or a fire test.

When asked if the lights were noticeable and easy to be seen a significant majority said yes. However, when asked if they heard the audio message the common answer was not until they were directly under it. This was due to the noise of the alarm and of other occupants within the area of evacuation, despite the fact that care had be taken to ensure that the message was played at the recommended decibel level, as described in Chapter 4. Of the occupants who did hear a clear message they all stated that it was a good idea but needs to be clearer and louder, noting that this could have undermined the actual effectiveness of the way-finding tool.

The main conclusion gained from the questionnaire was that the occupants did notice the way-finding tools, with the lights being the most effective, and believed that the audio messages would have been effective if the message had been louder and clearer. The other important information gathered was the fact that the occupants willingly admitted to only reacting to the alarm once it had been activated for a long period, just in case it was an alarm test, and that once they began to evacuate they tended to head towards the exit that the crowd was using.

7.6.12 Results

The three biggest factors that determine the level of efficiency of any evacuation are the time it takes for the occupants to react to an alarm, how long they wait from reacting to the alarm until they begin to evacuate from the building and most significantly, the routes that they adopted.

The results of the two experimental analyses were very different to each other. During the first trials on average the occupants waited 65 seconds before they became aware that the alarm was not a test, whilst during the second trial the average waiting time was reduced to 53 seconds. It was deduced that this reduction occurred due to the fact that the second trial was held on a day when it was not normal for the alarms to be tested, causing the occupants to become inquisitive and seek out an answer. The difference in behaviour between the two trials, when considering waiting times, was that over 95% of the occupants within the first trials had to be told by a fire warden to evacuate the building compared to a significant percentage of less than 5% during the second trials.

The contrasts between the reaction times in the two trials were also very significant with the average reaction time for the second trial being 29 seconds shorter than the first trial. As with the waiting time the decrease was in part due to the occupants becoming inquisitive/confused about the alarm and also due to the new way-finding equipment used. As stated within the questionnaire the majority of the occupants noticed the equipment and realised that it wasn't a faulty alarm/test, which helped to initiate the evacuation process reducing the reaction time. A reduced reaction time meant that the occupants were quicker to make a decision about evacuating, which included the choice of exit.

The behaviours of the occupants during the two trials changed significantly. During the first trial, the majority occupants chose to ignore the alarm and only began to evacuate once they had been told to by a fire warden, while in contrast, the majority of occupants during the second experiments reacted to the alarm quicker and without having to be told to by a fire warden. The changes is thought to have occurred due to the activation of the alarm of the second experiment taking place at a different time and day than the "normal" testing scenario.

The occupants also appeared to be calm and unstressed during the first experiment, with some occupants making jokes and smiling as they exited the building. The relaxed feeling contributed to the occupants taking longer to gather their personal items and lock their office doors before evacuating. Due to the change of day for the activation of the alarm for the second trial occupants were less relaxed and showed signs of increased inquisitive behaviours, leading to the majority of occupants evacuating the building in less time and without being advised to by a fire warden.

During the first trial the main exit used to evacuate the building was the main stairwell, known to most to be the main entrance to both the AGB and WR buildings. The second most common exit was the other main entrance that can be used to enter the WR building, with the other two exits being virtually ignored. This is in complete contrast to the exit choices of the second experiment, which was expected. Closing the main stairwell reduced the exit choice within AGB to only a single exit, however, there were still two possible exits to be used within WR, one which was common knowledge and another that was ignored during the first experiment. The predicted behaviour would be that the occupants would still ignore the unused exit and aim for the second main exit. However, the most used exit within the WR building became the secondary (ignored) exit from the previous experiment.

From the video analysis and questionnaire it became clear that the influence of the green LEDs upon the door and the phenomenon of herding behaviour [96] were the combined factors in the increased use of the exit. The initial occupants within the corridor would be the first to see the LEDs resulting in them using the exit, whilst the occupants behind would see that the exit was being used and use it themselves. Once there was a large enough gap between the occupants the door would close and the process would start again, proving the effectiveness of the visual way-finding tool.

The success of an evacuation is generally based on the total time it took from the activation of the alarm until the last occupant has left the building. As stated before, the differences between the two trials were the installation of audio and visual way-finding tools and the removal of the main entrance/exit to the building. In theory the removal of the main stairwell should increase the evacuation time for the building, however, this was not the case. The overall evacuation time for the first trial was 165 seconds with an average walking speed of 1.2 m/s. The evacuation time of the second experiment was significantly lower for both the AGB and WR building at a value of 126 and 138 seconds respectively. However, the average walking speeds were reduced to 0.93 m/s for the AGB and 1.08 m/s for the WR building.

It was concluded this phenomenon occurred during trial two due to the following:

Factor	Effect
Use of secondary exits	Reduced walking distance
	Reduced urgency to rush to the exit
Experiment held on a different day to alarm test	Made occupants more inquisitive and uneasy leading to a more effective decision making process

Installation of way-finding tools	Helped occupants find the nearest exit
	Provided more information about the evacuation
	"Odd" nature of tools focused occupants behaviour due an increase state of awareness.
Learning effects	Some occupants may have been more relaxed due to taking part during the first trial. (Note: both trials were unannounced)

Table 43: Possible factors affecting the office evacuation results

7.6.13 Discussion & Conclusion

The trials conducted provided detailed data on the effect of providing a wide range of information to occupants via the use of way-finding tools, while highlighting the effect on the occupant's behaviour during an evacuation. Furthermore, the experiments demonstrated how the removal of a building's main egress route could influence the movement speed, movement paths and behaviours of the occupants. It may be argued that the results cannot be applied for every possible egress situation that could occur during an evacuation of a building. However, these experiments were conducted to determine whether or not the use of way-finding tools could affect the evacuation process of the occupants who had no prior knowledge of the evacuation and the use of the way-finding tools.

The dominant behaviour present throughout the first trial was the use of the main exits from the building while ignoring the secondary egress routes available. However, the analysis suggests that the exit choice of the occupants is also influenced by the exit choices made by others, whereas the dominant behaviour present through the second trial was taking time to investigate the closure of the main exit while discussing with other occupants about the possible egress routes still available.

The main purpose of the experiments was to test whether it is possible or not to influence an occupant's exit choice, using way-finding tools, when the preferred route was unusable. Of the types of visual tools tested the green LEDs were found to be the most effective at providing information to the occupants, while the red LEDs initially confused the occupants and took extra time to decipher. Of the types of audio tools tested, the speaker providing information on the location of an available exit was better received and understood than the speaker providing information on the closure of an exit, which occupants misunderstood to be that the final building exit was closed, not the exits upon the level.

The trials tested how the different way-finding tools would work within a simple building environment yet it is unknown how they would work within a more complex situation, for example a shopping centre. The audio tools may be received more openly at an installation within a building with a large number of people with the lights being provided as a secondary evacuation tool. On the other hand, the visual tools may be more efficient within a situation where the audio tools may be contaminated by other audio sources or may be affected by reverberation/acoustic echoing.

The experiments conducted showed that it was possible to influence an occupant's exit choice, using way-finding tools, when the preferred route is unusable. The presence of the way-finding tools provided occupants with extra information that allowed them to assess the situation they were in and helped guide them away from the unusable exit and towards an exit that would eventually lead them to safety with as little confusion as possible.

The experiment stressed the importance of providing occupants with up-to-date information on the situation they are in during an evacuation. The efficiency of the way-finding tool will be easy to increase by providing the occupants with training concerning the way-finding tools within the building on an annual or bi-annual basis.

The purpose of this experiment was to examine the ability of way-finding tool and how they can be used to influence the final exit choice of occupants when the preferred means of escape is removed without warning.

It is postulated that installation of a sensor-linked evacuation system is the future of egress way-finding tools and this experiment has helped to demonstrate the importance that these way-finding tools may have in the future.

7.7 Summary

The above chapter discusses the empirical data required in the development of the I.D.E.S. and the experiments that were conducted to gain this data.

The data gathered from Experimental Series 1 included the phenomenon of learning effects on the behaviour of the occupants and how it affect the occupant's interaction with the experimental rig and each other.

The reliability of the results produced by the live evacuation may include certain issues such as the behaviour of the occupants being different to those who find themselves within an actual evacuation. It is possible that the occupants were more calm and relaxed as they were given relevant information prior to the experiments and hence were well informed, which will not be the case in most real world evacuations. They will also be more willing to wait and make room for others to pass, as they are aware that they are not at any immediate threat from fire or smoke. Another issue is that the reliability of the results will have been affected by the repetition of the experiment. It is natural that the more often a person is introduced to a given test environment the more comfortable they become, thus reducing their urgency to evacuate. Finally, the occupants will tend to develop effective exit strategies that they will continue to use over and over again in the experiments. This would not occur within a real evacuation.

The data gathered from Experimental Series 2 demonstrated how the installations could influence the movement speed and patterns of movement of the occupants who find themselves in an unknown situation and environment. The analysis data showed that the movement speeds produced during the experiments are similar to those presented in previous studies conducted. However, the data suggest that the movement speed is not influenced by the type of floor material used or the presents of a gradient. Hence, the present of smoke and the lack of lighting seem to be the defining factors that affect the speed of the occupants during an evacuation of a tunnel.

The dominant behaviour present throughout the experiments was the use of the tunnel walls by the occupants to help them navigate through the smoke-filled environment.

The main purpose of the experiment was to analyse the effect of different emergency exit designs and way-finding installations based upon their ability to attract the participants. Of the installations tested, the door equipped with the loudspeaker, which broadcasted an alarm signal and a voice message, was found to be the most effective at attracting the participant to the exit. The least effective was the combination of a continuous green and white source with a strong halogen lamp. This installation was misinterpreted by many of the participants as a train even though the lights were visible through the dense smoke, it led to the participant avoiding using the exit due to the uncertainty associated.

The experiments stressed the importance of using way-finding tool around an emergency exit and the effects each design had. The use of smoke during the experiment showed that certain set ups of way-finding may be confusing for participants, e.g. continuous lights, while showing other tools could reduce the confusion, e.g. flashing green lights. The use of a loudspeaker near the emergency exit was found to be highly effective at attracting participants to use the door, independent of the side of the tunnel they were walking on.

The data gathered from Experimental Series 3 provided detailed data on the effect of providing a wide range of information to occupants via the use of way-finding tools, while highlighting the effect on the occupant's behaviour during an evacuation. Furthermore, the experiments demonstrated how the removal of a building's main egress route could influence the movement speed, movement paths and behaviours of the occupants. It may be argued that the results cannot be applied for every possible egress situation that could occur during an evacuation of a building. However, these experiments were conducted to determine whether or not the use of way-finding tools could affect the evacuation process of the occupants who had no prior knowledge of the evacuation and the use of the way-finding tools.

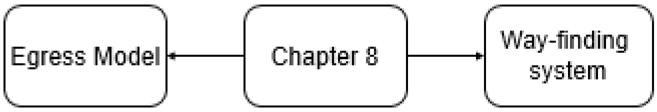
The experiments conducted showed that it is possible to influence an occupant's exit choice, using way-finding tools, when the preferred route is unusable. The presence of the way-finding tools provided occupants with extra information that allowed them to assess the situation they were in and helped guide them away from the unusable exit and towards an exit that would eventually lead them to safety with as little confusion as possible.

The experiment demonstrated the importance of providing occupants with up-to-date information on the situation they are in during an evacuation. The efficiency of the way-finding tool will be easy to increase by providing the occupants with training concerning the way-finding tools within the building on an annual or bi-annual basis. It is postulated that installation of a sensor-linked evacuation system is the future of egress way-finding tools and this experiment has helped to demonstrate the importance that these way-finding tools may have in the future.

The new data gathered from all three experiments allowed for the development of way-finding tools within CRISP for use within the egress prediction models as well as the models used to simulation the experiments *A Priori & A Posteriori* as part of the development of the behavioural sets available within the model.

The following chapter will take the existing CRISP program and try to predict the outcome of the experiments discussed above within this Chapter, as well as the development of the coding used as part of the models. The final test for the program will to be carry out a feasibility study assessing the potential of the system to be used within a building that will be based on an existing office tower and a series of evacuation scenarios.

8 Model development



Two of the main critical functions required to be provided by the Information Driven Evacuation System will be its ability to predict the development of a fire and the movement/ behavioural choices of the occupants while they attempt to evacuate to a “safe” place. The program’s ability to predict the development of a fire has been covered as part of the Dalmarnock fire tests [56] with the result produced comparing well to the actual results provided by the fire and the research conducted by Dr Sung Han-Koo [12]. Hence, the following chapter will focus on the functionality of the egress side of the system.

Within this chapter the focus will be on the egress predictions CRISP, while demonstrating how the empirical data gathered as part of the evacuation experiments conducted was incorporated within the programs source code. The adapted source code will be used as part of a feasibility study to demonstrate how the system would work in practice during a variety of evacuation scenarios from a high rise office tower.

8.1 Functionality requirements.

In order for CRISP to be used as the part of the I.D.E.S. it must be able to predict the influence of way-finding tools on the occupants’ decisions and exit choices as they egress through the building/area. The required functionality was, prior to this research, not included within the original source code. As stated within Chapter 7, new data was gathered from three experiments with the purpose of developing the use of way-finding tools within CRISP for use within the egress prediction models as well as the models used to simulate the experiments *A*

Priori and A Posteriori as part of the development of the behavioural sets available within the model.

While there are fire engineering research facilities currently conducting evacuation experiments and collecting significant data on human behaviour during evacuations, gaining access to the required level of information needed to develop a prediction model is limited. Therefore, even though the experiments conducted for this thesis are not as ground-breaking as other experiments conducted in recent years, for example the Dalmarnock fire tests [56], they were appropriate as they did serve the purpose of providing the information required to develop the prediction models. The new functionality developed, as part of this thesis, is described in detail further on within this chapter; however, the following is a quick overview.

Experiment Series 1 lead to the inclusion of "learning affects" and "data sharing" between occupants within the behavioural sets used as part of the basic CRISP model. Yet, it should be noted that the processes within these sets were more robotic in nature than compared to real life and led to more of an expected delay rather than actually learning or sharing data during an evacuation.

Experiment Series 2 lead to the initial development of the more effective way-finding tools used and was used as a feasibility analysis to determine if it was possible to influence an occupant's exit choice/route using way-finding tools in both a real life situation and within the modelling program.

Experiment Series 3 combined all the information gathered during the first two experiments and further tested the influence of way-finding tools. As well as studying the effects of removing the most desired/common route from a building and whether positive or negative based information has more of a measurable influence an occupant's decision making.

8.2 Implementation via Evacuation Experiments

The experiments covered above, under Chapter 7, were conducted to not only undertake the study of the occupant behaviour as they completed their evacuation but were also conducted to provide empirical data that could be used to test and modify the CRISP source code so that it could be used as part of the I.D.E.S. The following describes how the program was implemented within each experiment, how each experiment was used to development the source code, the results provided and the discussion and conclusions gathered.

8.2.1 Experiment Series 1

As part of Experiment Series 1, CRISP was tested to see if could be used to calculate the flow rates of the participants at other evacuation heights not tested. To see if the predictability capability of the program was correct, the values of the flow of the train and tunnel from experiment 2 (1.4m evacuation height) were used to calculate the number of participants that could evacuate from the train and tunnel within the time period of 300 seconds. Once the number of occupants was calculated these values would remain as the standard for the other evacuation heights modelled. To ensure that the program can predict the flow rate the values calculated for live data for the evacuation height of 0.75m were compared to the values produced by the model.

The results from the 3rd of December were chosen because there appeared to be no significant effect on the results caused by changing the floor material within the tunnel. Therefore, the results gathered with a concrete floor were used, as CRISP did not incorporate a rough stone floor setting for floor material.

The model geometry for this study was based upon the experimental set up for scenarios 2 and 6, where the only difference between the scenarios was the evacuation height from the train on to the tunnel floor. The models were created before the experiments were run.

Due to the fact that CRISP is a 2D model the default view of the simulation geometry is from a bird's eye view, as per Figure 66. The critical change in floor height between the tunnel and the train is not visible here, but was created by adjusting the floor height of the tunnel, before each model run, to the required evacuation height.

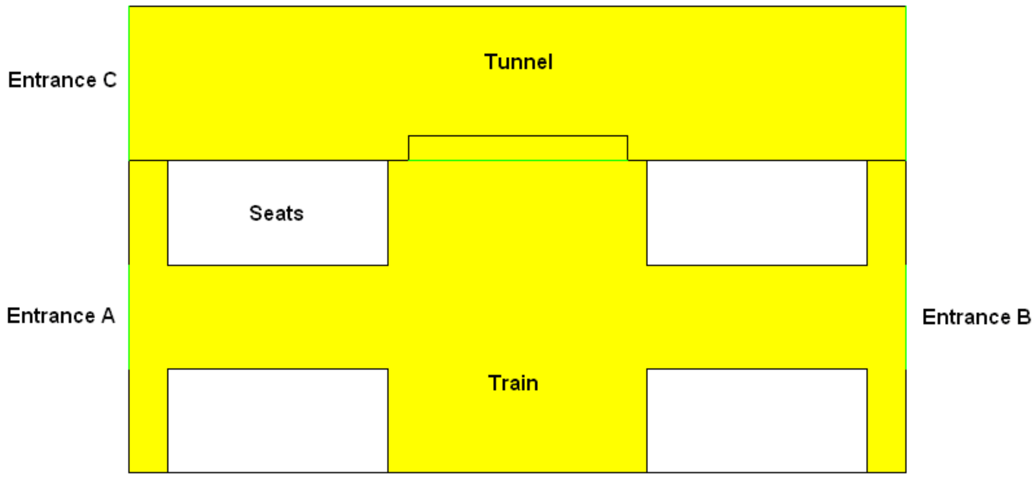


Figure 66: CRISP model 2D simulation view of experiments

Obstructions were used to create the effects of having the seats within the train. This reduced the aisle width to the required value and created the exit lobby as described in table 44. The program was used in "Evacuation mode" (as discussed within Chapter 6) which meant that the Monte-Carlo control for fire growth was not used.

As the time duration of each experiment was 5 minutes the CRISP models were set to a time limit of 300 seconds and the total number of occupants who evacuated the model was recorded and used in the calculation of the flow rates. Each model was run for 1,000 iterations and the results of overall times, average evacuation time and average flow rates were calculated.

For the CRISP models the following assumptions were made:

Average flow rate used was 1.2 m/s
Average height of the occupant used was 1.75 m
All occupants will react immediately to the whistle at the start of the experiment
There will be bunching and queuing effects experienced by the occupants
Occupants in the tunnel will provide space for occupants within the train to evacuate
180 people will be able evacuate from the train within the time limit
240 people will be able evacuate from the tunnel within the time limit

Table 44: CRISP modelling assumptions.

8.2.2 Code Development Experiment Series 1

The purpose of the models was to see if CRISP could replicate the flow rates of the live experiments and to examine the effect of varying evacuation heights on the flow rates of the occupants. As per above, the default CRISP model was not coded to account for the effects of having occupants evacuate off a drop.

With the constraints of the CRISP methodology it was apparent that the easiest ways to represent a change in evacuation height was to either reduce the effective width of the exit or to use a ramp to reproduce the time taken to get from the train to the tunnel floor. However, these approaches would require the modeller to have prior knowledge on how the different evacuation heights affect the flow rate. A purpose of this study was to investigate the *A Priori* prediction of the effects of a change in height on the flow rate, so these approaches would not provide a direct solution to the problem. Therefore, the CRSIP was modified to accommodate the effects of the change in evacuation height based upon the modeller's engineering judgement. The following assumptions were adopted for the basis of the modified code:

For simplicity for a starting function, it was predicted that the effects of evacuation height on occupants flow rates will follow a similar path to that of negative exponential graph, i.e. occupant flows will decrease in a negative exponential shape. Beyond a certain height threshold the flow rate drops to zero, i.e. the descent is too high for anyone to attempt. Thus the higher the evacuation height the more sensitive the flow rate will be to small changes.

The script within the CRISP source code that calculated the flow rate of the occupants through an exit is found within the Vent.for Fortran file under the subroutine set_vent_pos(v,x). The formula used to calculate the time it takes for an occupant to transit is:

```
time_per_transit(v) = 1.0 / (bodflow * eff_width)
```

Equation 1: CRISP occupant transit time

The "bodflow" (person/metre/second) is a constant value that is set by the programmer and the chosen value was from the SFPE book. The effective width is calculated by the program based upon the input building geometry set by the modeller.

The first requirement of the edited code will be to calculate whether or not there is a change in floor height between adjacent zones associated with each vent. If the change in floor height was zero then the program can use the original code to calculate the time_per_transit. If the change in height was not zero then the following formula will be used by the program to calculate time_per_transit.

```
time_per_transit(v) = ((1.0 / (bodflow * eff_width))*exp(vert_drop))
```

Equation 2: Edit occupant transit time.

The parameter "vert_drop" is constrained to be negative, thus the factor of exp(vert_drop) was chosen as the modeller hypothesised that the flow rate of occupant from the train to the tunnel floor would decrease at an exponential rate as the height difference increased. This equation incorporates the effects of both the evacuation height and exit width on the flow rate, which would be two of the most significant factors during an evacuation.

Comparing the original code and the edited code shows the effect of evacuation height on the value of time_per_transit (Figure 67):

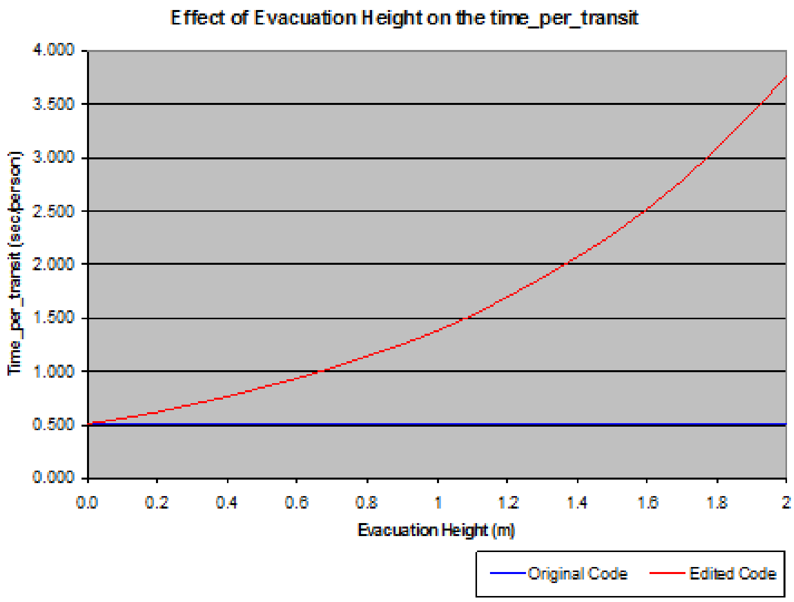


Figure 67: Comparing original code values to edited code for the time_per_transit

However, when the simulation was run with the new code the results produced were nowhere near the required results (Figure 68).

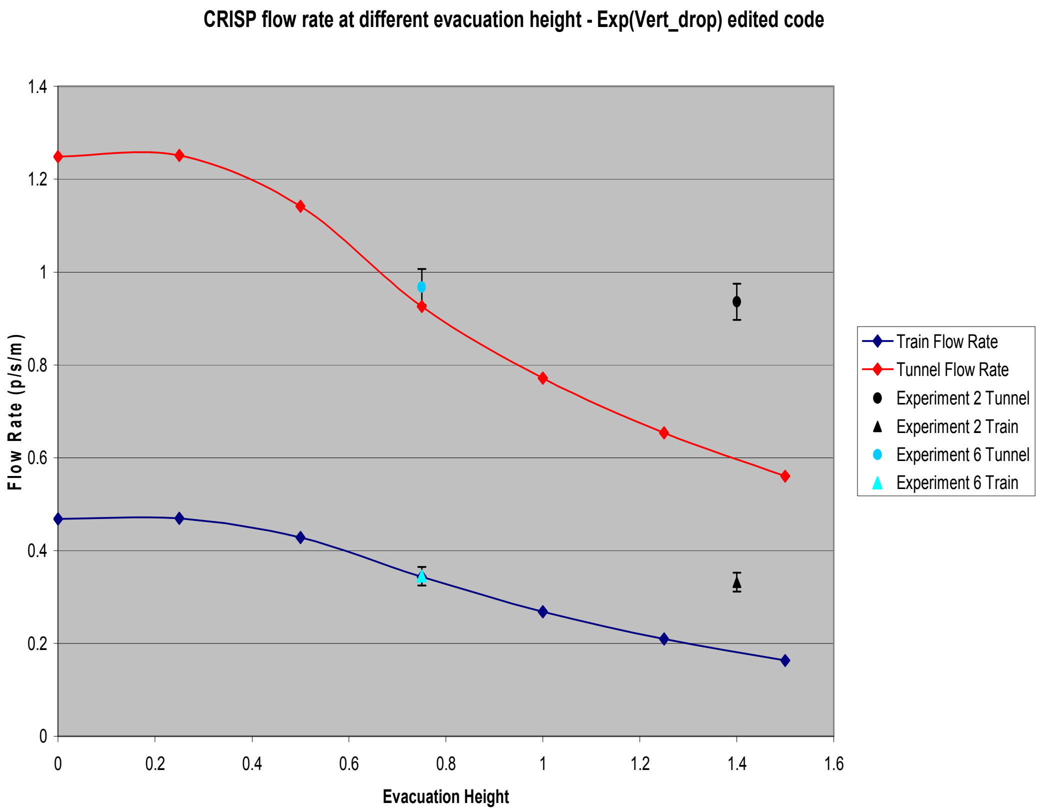


Figure 68: Comparing original code values to edited code for the time_per_transit

Even with the error bars only the value for the flow at 0.75 m within the train was close to the value produced by the model. Therefore the original assumption of using the factor exp(vert_drop) was incorrect and a new factor would be needed. When looking at the live data it appeared the flow followed a polynomial trend with an order of magnitude of 2.

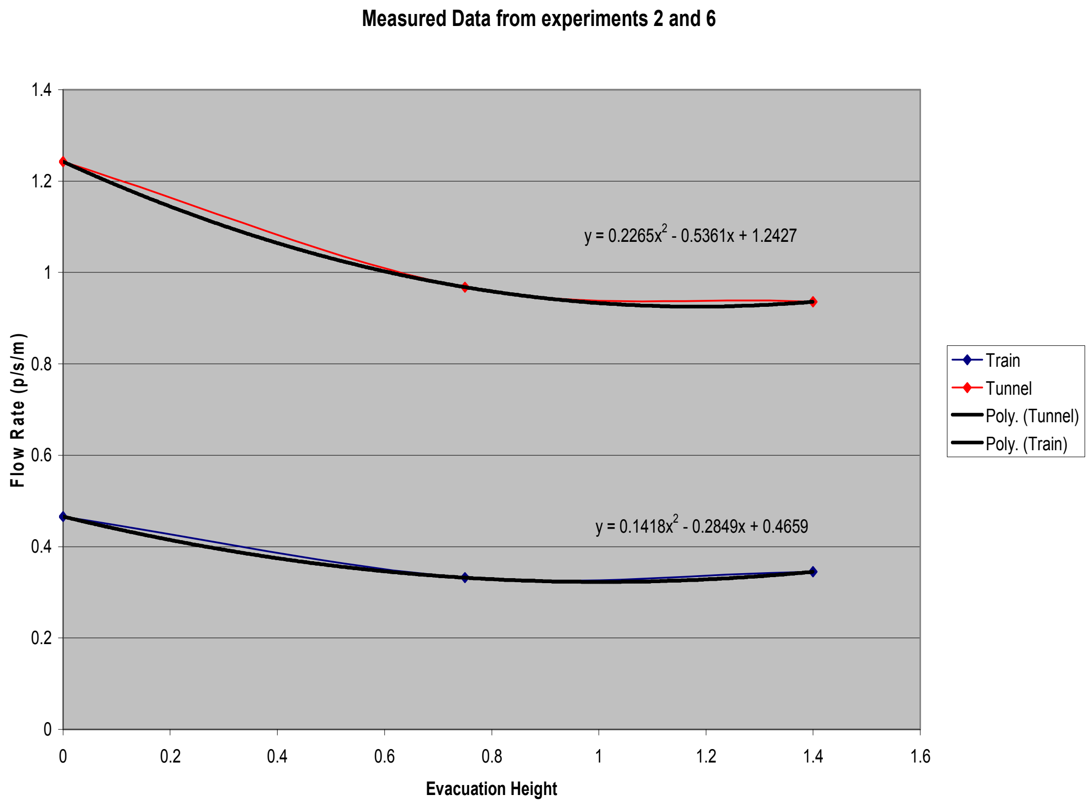


Figure 69: Comparing original code values to edited code for the time_per_transit

Therefore, the new factor for the CRISP source code would need to be of a similar equation in the form of:

Time_per_transit(v) = +/- A x (vert_drop)2 +/- B x (vert_drop) + C\

Equation 3: Required equation for CRISP

The factor of C was easy to calculate as it was the value of time_per_transit at an evacuation height of zero, which is calculated by the original code.

```
time_per_transit(v) = 1.0 / (bodflow * eff_width)
```

Equation 4: Equation for finding factor C

Therefore, what followed was a series of trial and error modelling runs using the above equation and the value of the flow at 1.4m (0.936 p/s/m for the tunnel, 0.345 p/s/m for the train) with varying factors for A and B. The final code used was:

```
time_per_transit(v) = -0.75*(vert_drop**2)+1.75*(vert_drop)...
+(1.0 / (bodflow * eff_width))
```

Equation 5: Adjusted CRISP equation for time_per_transit(v)

8.2.3 Results Experiment Series 1

The results obtained with the pre-existing (original) version of the code, prior to any modification for change of evacuation height, are presented in Table 45 and Figure 70 below.

	Evacuation Height (m)						
Flow Rate (p/s/m)	0	0.25	0.5	0.75	1	1.25	1.5
Tunnel	0.468	0.470	0.469	0.469	0.469	0.469	0.469
Train	1.249	1.253	1.250	1.251	1.251	1.250	1.250

Table 45: CRISP calculated flow rates at varying evacuation heights

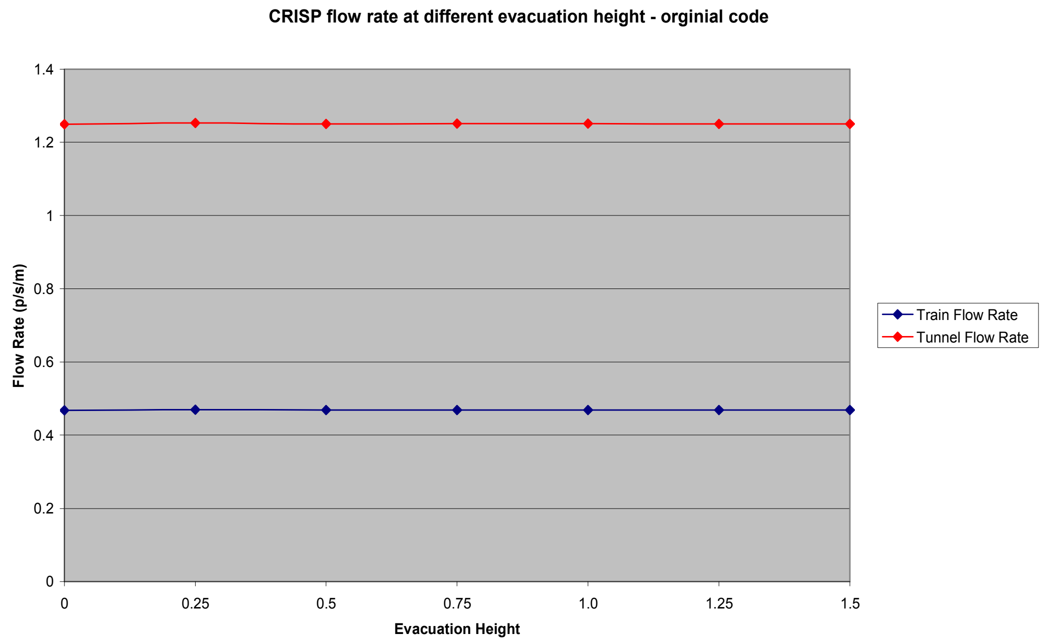


Figure 70: Graph comparing tunnel and train flow for original code

As seen from the graph and the table above, the flow rates within the tunnel and train were generally at a fairly constant value across all evacuation heights (though note that these are not deterministic models but the output of the Monte Carlo simulations each involving 1000 cases). This is consistent with the fact that the original code does not take into account the effects of change of evacuation height on the flow rate. Therefore, in order to allow CRISP to have the ability to effect an occupant's evacuation off a vertical drop the source would require alteration.

After development of the new source code was completed the scenarios were remodelled within CRISP. The results produced are shown below in Table 46 and Figure 71.

Evacuation Height (m)	Model flow rate (p/s/m)	
	Train	Tunnel
0.00	0.466	1.243
0.25	0.467	1.246
0.50	0.414	1.103
0.75	0.361	0.967
1.00	0.337	0.910
1.25	0.334	0.904
1.50	0.332	0.899

Table 46: modelling values of flow rates for all evacuation heights

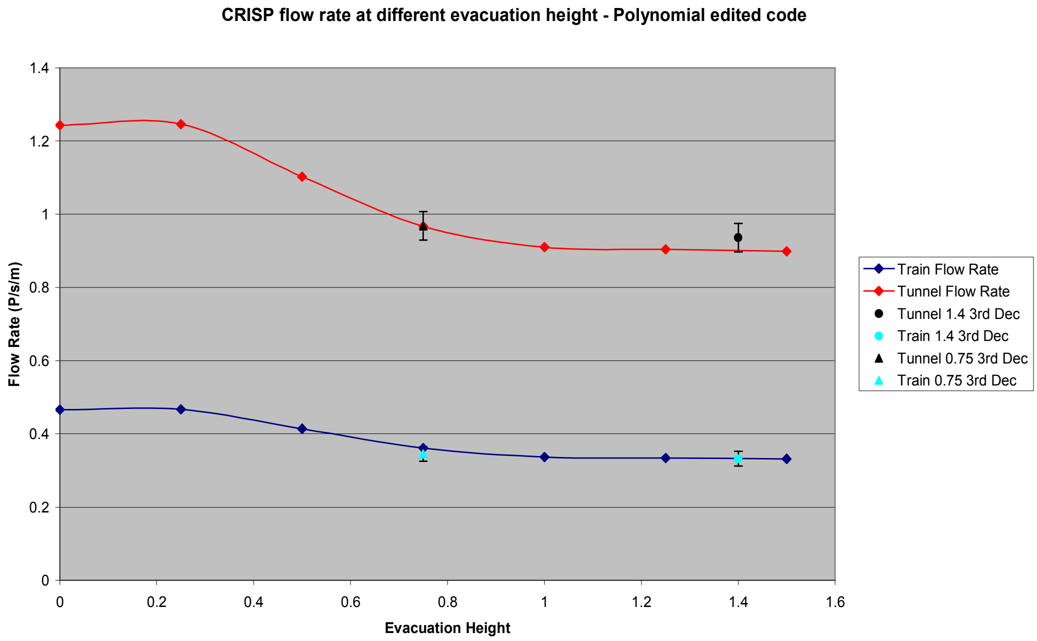


Figure 71: Flow rates produced by new source code due to varying vertical drop heights

The error bar within Figure 71 represents the flow rate determined from the live evacuations that were used to calibrate the source code effect on the flow rates. The new code was then used to model the effects on the flow rate and evacuation time of the occupants cause by varying the vertical drop they were required to descend during the evacuation (Figure 72 and Figure 73).

The following graphs compare the average modelled flow rate against the average total evacuation time for both the train and the tunnel.

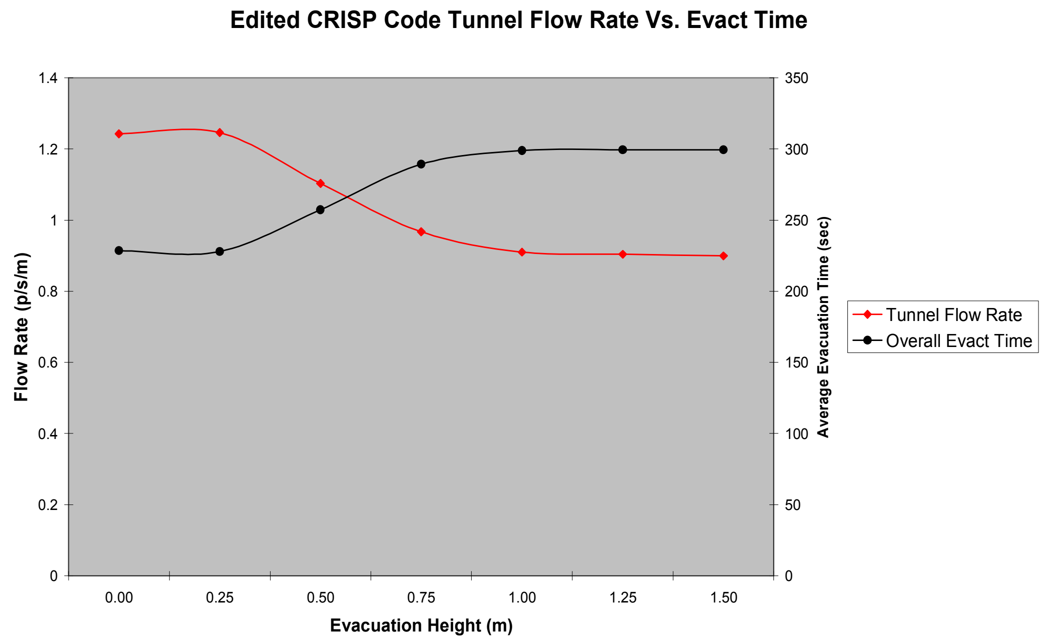


Figure 72: Comparing the tunnel flow rate and evacuation time for new source code

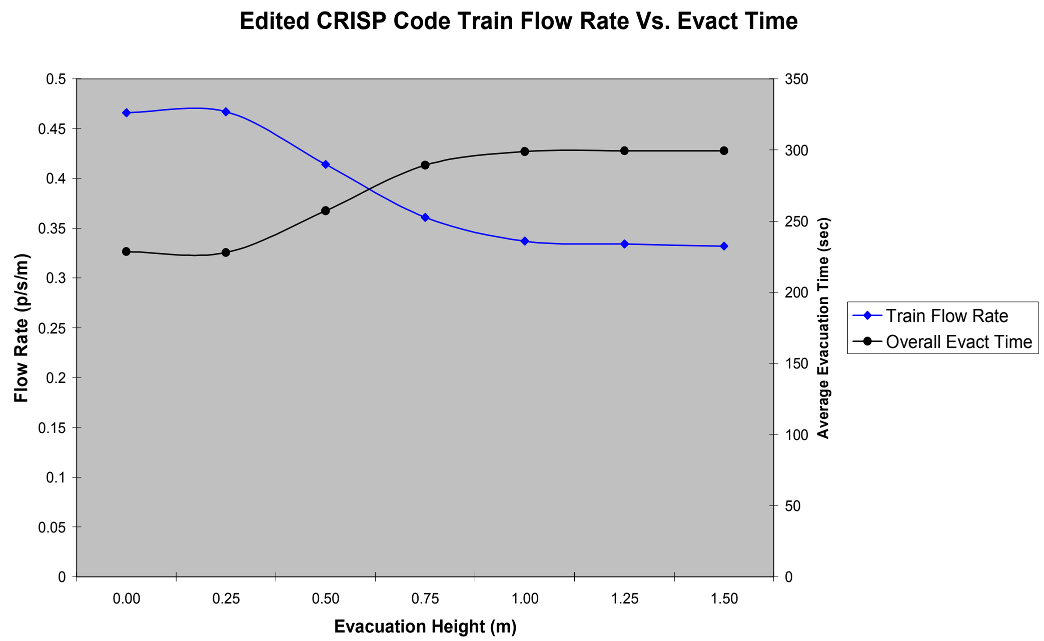


Figure 73: Comparing the train flow rate and evacuation time for new source code

8.2.4 Discussion and conclusions Experiment Series 1

The results shown in Figure 71, produced by CRISP, reveal that as the evacuation height increases, the flow rate per metre significantly decreases, leading to longer evacuation times. Between the evacuation heights of 0.25 and 0.5m the average flow rate begins to decrease, which is expected as different occupants will react differently to the changes in height, where shorter occupants tended to be more hesitant to jump down into the tunnel compared to taller occupants.

At lower evacuation heights the mode predicted a significantly increased in the queuing of the occupants. While on the other hand, higher evacuation heights lead to longer queuing times within the train, with occupants taking longer to descend to the tunnel floor.

Due to the live evacuations having a time limit of 5 minutes, the models were also run to the same time limit. This therefore meant that at the higher evacuation drops, with larger amounts of occupants at the end of the simulation, occupants were unable to complete the evacuation and were still within the train at the end.

The models showed that the evacuation of the train dictates the overall evacuation time. Towards the upper range of evacuation heights the evacuation times become the same (due to the 5 minute limit) and hence it appears that there is no significant effect generated by queuing at lower evacuation drops.

As shown previously, it was proposed that the CRISP code adopt an exponential factor to modify the time it takes for an occupant to evacuate from the train as a function of the height change. However, this factor did not provide a satisfactory fit for the live data, as it tended to delay the egress too quickly. After analysing the live data it appeared the flow rates followed a polynomial trend significantly better than an exponential trend. Therefore, a polynomial equation was used as the new factor in the edited CRISP code. The new factor polynomial factor assumed by the modeller to describe the impact of change of height was chosen due to its simplistic mathematical properties.

The experimental data points that have been compared seem to show that the model is successful at replicating the flow rate for both the train and tunnel occupants. Errors could arise with other data points due to the following issues related to the modelling assumptions and artificial constraints of the experiment versus the real world.

The modelling issues included using an incorrect number of occupants for the experiment as occupants would complete multiple evacuations during a given experiment, using an incorrect average flow assumed by the modeller, an assumption that all initial occupants within the tunnel will evacuate before the end of the simulation time (5mins) and finally, incorrectly assuming that the number of occupants would be able to evacuate the train within the time limit.

As shown in Figure 71, the current model was able to provide representative simulations of the flow rate in both the tunnel and train.

The purpose of this experiment was to examine the effects of different experimental evacuation scenarios on the exit densities and flow that occurred during an evacuation within a stopped train carriage and the corresponding tunnel. The capabilities of CRISP were also tested as part of these experiments to determine its ability to be used within the feasibility study for the proposed sensor-linked system. The second stage of experimentation, as discussed within Chapter 7.5, will focus on the use of way-finding tools during a tunnel evacuation and the ability of CRISP to use the way-finding tools, which will be a part of the sensor-linked system, to predict the effects of the tools on the flow paths and decision-making process of the occupants.

8.2.5 Experiment Series 2

Experiment Series 2 provided the opportunity to run a series of *a priori* models to further test the predictive capabilities of the modelling program CRISP. The process involves predicting the overall effects of the different way-finding tools on the flow rate and movement of the occupants while studying their exit choice.

The scenarios simulated by the models are listed below in Table 47. Scenario 1 was used as the base case for the simulation; while Scenarios 2 and 4 were chosen as it was assumed prior to the experiments that these set-ups would be the most efficient combinations of way-finding tools for attracting the participants towards the emergency exit.

Scenario	Way-finding Tool	Descriptions
1	2	Emergency Sign
2	2,3	Emergency Sign + Green Flashing Lights
4	2,4	Emergency Sign + Loudspeaker

Table 47: Scenario chosen to be modelled.

The cross-section and dimensions of the models were based upon the values stated in Table 25. As the time duration of each experiment was 15 minutes the CRISP models were set to a time limit of 900 seconds and the time taken for occupants to either exit along the left or right hand wall was recorded. Each model was run for 1,000 iterations and the results of overall times, average evacuation times and average flow rates were calculated.

The program was executed in the mode known as “evacuation”, which means that the chosen alarms are active at the start of the simulation. Therefore, this reduces the pre-movement behaviours that form part of the overall evacuation time, leaving the occupants with only one required decision to make, the amount of time they will wait before beginning to evacuate. The evacuation mode also removes the “fire” or smoke from the simulation. Therefore, to recreate the effects of smoke within the tunnel, like the actual experiments, a constant optical density was applied to the model to recreate the effects. The model uses the optical density to reduce the walking speeds of the occupants within the model to a slower rate to simulate the effects of reduce visibility due to the development of smoke.

As the models were conducted *a priori* the value used for the optical density was calculated using the following equations and standard values required by the Swedish design codes [91]. It should also be needed that due to the randomness of the system used by the Lund research team it was not possible to predict the smoke levels in advance within the town, hence the standard values were used.

Equations:
S = C/K
D = K * Log10 E = 0.42429
Code Required Values:
C = 3 (Coefficient for viewing a sign)
S = 3 (Visibility Factor Swedish Regulations)
K = 1 (Light Extinction coefficient)
Optical Density Value:
D = 0.42429

Table 48: Calculation of the optical density

Hence, as CRISP is a zone model, providing the program with a constant optical density creates the effect that both zones (hot and cold) are filled with smoke and the occupants will behave according to the conditions. However, before the models were simulated, extra code was required to be added to the program in order to create the way-finding tools used within scenarios 2 and 4, the flashing light and loudspeaker respectively. Hence, as within Experiment Series 1, in order to allow CRISP to have the ability to use way-finding tools to influence an occupant's flow path and decision-making process, the source would require alteration.

8.2.6 Code Development Experiment 2

The computer language used to create CRISP is FORTRAN 95 and in order to include the new types of alarms into the simulations required an edit of the source code of the program was needed. The original source code did provide the programmer with the ability to have a sounder activate with an alarm, however, the noise provided by the sounder would be able to be heard throughout the entire simulated building and not a specific section as used in the experiments. The use of lights as a directional tool during an evacuation, based on the location of smoke with the simulation, was also not present within the original code. Before addressing the issues with the loudspeaker and way-finding tool the required alteration to the program to use just an emergency exit sign (Scenario 2) was developed first.

In order to simulate Scenario 1 the occupants were required to react to the smoke without the use of detectors or a warning sound, which are normally used to facilitate evacuation. Hence, when the initial simulations were executed the occupant within the tunnel did not show any reaction and waited the entire simulation in the same spot. The issue was addressed by altering the initial waiting time of the occupants to 45 seconds. The 45 seconds was used to simulate the fire fighter intervention to initial egress of the occupant within the tunnel, during the experiments, asking the participant to begin their evacuation or if they would like to abort. If the simulated occupant still stayed in the same spot, it was assume they had "aborted" the evacuation.

Scenario 2 required the use of green flashing lights to attract the participants towards the emergency exit. CRISP was not created with this function in mind and therefore a new part of the source code was required to be created. Within the code a new alarm type defined as "WFL" (way-finding lights) was created. The new case file (Figure 74) used the following variable to recreate the effects of using a flashing light.

```
case(WFL)
    read(dataline,*) dummytext,detroom(d),det_link(d),det_fail(d), SamDOD1(d), SamDOD2(d), Svent(d)
```

Figure 74: Input variables for way-finding lights within CRISP

Variable Name:	Description:
Sam DOD1	the degree of difficulty to open door between Room A and Room B
Sam DOD2	the degree of difficulty to open door between Room B and Room A
Svent	The vent where the lighting system is installed

Table 49: Breakdown of input variables for way-finding lights within CRISP

The degree of difficulty (DOD) is the variable that determines how easy the door is to travel through based upon the environmental conditions within the building. The higher the value of DOD the less reluctant the occupants will be about using the vent to evacuation, hence, if the vent had a value within the range of 1 – 3 they would use the exit and any value higher they would ignore the exit. Therefore, to simulate the green flash light a value of 1 – 3 was used by the code to represent the green light and a value of 4 – 5 was used to represent a red light (not used in the experiments).

As stated, the DOD is determined within the code by the environmental conditions within the building (i.e. the presence of smoke) and the code for Svent uses the room of the fire's origin to determine the DOD. Therefore, as the model has a constant optical density the room of the fires origin is the tunnel itself. This meant that the DOD for the emergency exit from the simulation was at a value of 5 at the very beginning of simulation. Hence, when using the WLF code command within the simulation allowed the user to redefine the DOD of the vent to a value between 1 and 3 or in other words to simulate a green flashing light. The Svent code is provided below in Figure 75.

Scenario 4 required the use of a directional loudspeaker to encourage participants to walk faster and in the direction of the emergency exit. The sounding capability of the original CRISP provided a sound that can be heard throughout the room which the detector was installed in. As the experiments were within a tunnel this meant the participant within the simulation could hear the loudspeaker from anywhere within tunnel, which did not accurately simulate the actual experiments. Hence, a new sounder alarm type was defined by the user to simulate the directional speaker used in the experiments.

```
v = Svent(d)

 if (det_link(d).eq.2) then
            r = fire_origin

 else
            r = detroom(d)

 endif

   if (tenab(r).eq.0) then
        currentDOD(v,1) = min (SamDOD2(d),5)
        currentDOD(v,2) = 5

    elseif (tenab(r).eq.1) then
        currentDOD(v,1) = min (SamDOD2(d), 5)
        currentDOD(v,2) = 5

    elseif (tenab(r).eq.2) then
        currentDOD(v,1) = min (SamDOD2(d), 5)
        currentDOD(v,2) = 5

    elseif (tenab(r).eq.3) then
        currentDOD(v,1) = min (SamDOD2(d), 5)
        currentDOD(v,2) = 5

    elseif (tenab(r).eq.4) then
        currentDOD(v,1) = min (SamDOD2(d), 5)
        currentDOD(v,2) = 5

    else
        currentDOD(v,1) = min (SamDOD2(d), 5)
  endif

return
end
```

Figure 75: Code for way-finding lights within CRISP

As stated above the sound function (alrm_nse(d)) created a noise throughout the entire tunnel instead of within a certain directional zone. Hence, to counteract this occurring during the simulation a new code was written so that the sound would only be applied within the designated zone stated in the building geometry file. Occupants hear the noise of the alarm only when they are near its location.

```
case(Sounder)
     write(*,14) j,detroom(j),roomname(detroom(j)), alrm_nse(j), Sroom(j)
```

Figure 76: Input variables for sounders within CRISP

Essentially, the new sounder alarm code took the original sound code and applied the noise only to a section of the building geometry. The sounder code was applied to a conical shaped geometry with the purpose of attracting the occupants towards the emergency exit. Below in Figure 78 and 79 are the new code used and the conical shaped zone that was affected within the tunnel.

```
do d=1,detects
      r = detroom(d)
 if (Sroom(d).eq.r) then
                    alrm_nse(d) = sounder_dB(d)
 else
                    alrm_nse(d) = silence_dB
 endif
 Enddo
 return
 end
```

Figure 77: Code for sounders within CRISP

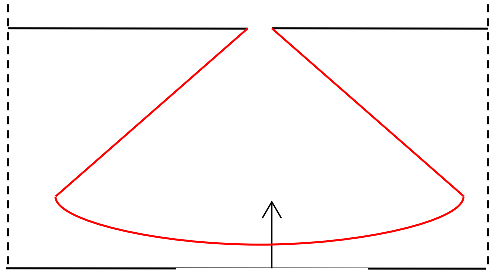


Figure 78: Sound zone produced by CRISP

The area of the sound zone provided by CRISP within Figure 78 represent the impact of the sound that is coding within the programme.

8.2.7 Results Experiment Series 2

The results provided by the simulations were used to determine the movement speeds of the occupants inside the smoke-filled tunnel. The movement speed for the models were calculated for each participant by dividing the travel distance by the total evacuation time, including the duration of the stops made, if any, during the evacuation. Unlike with the live evacuation experimental results, the movement speeds were calculated for the entire tunnel as a whole and not in three sections.

Scenario	Average Walking Distance (m)	
	A	B
1	180	188
2	180	184
4	180	182

Table 50: Average walking distance produced by CRISP

Comparing the results of the models to that of the experimental data analysed by Lund University, shown in Table 51 & Table 52: Lund University movement speed path A and path B it can be seen that the effects of having a constant optical density in the simulation affects the movement speeds of the occupant and produced values similar to that of the experiment. The small difference between the movement and modelling speeds could be explained by the fact that only 25% of the participants in the experiment paused during their evacuation, for an average time of 14 seconds. Hence, 75% of the participants were focused on evacuation and headed toward the opposite end of the tunnel without pausing, meaning that their movements were more focused and dependent on visual factors rather than behavioural factors.

Scenario	Movement Speed (m/s) Path A			
	Min	Max	Mean	Std
1	0.583	1.659	1.019	0.168
2	0.502	1.603	1.004	0.177
4	0.534	1.585	0.994	0.171
Live	0.477	1.563	0.920	0.247

Scenario	Movement Speed (m/s) Path B			
	Min	Max	Mean	Std
1	0.542	1.614	0.982	0.164
2	0.344	1.651	0.999	0.177
4	0.430	1.565	0.991	0.169
Live	0.477	1.563	0.920	0.247

Table 51 & Table 52: Lund University movement speed path A and path B

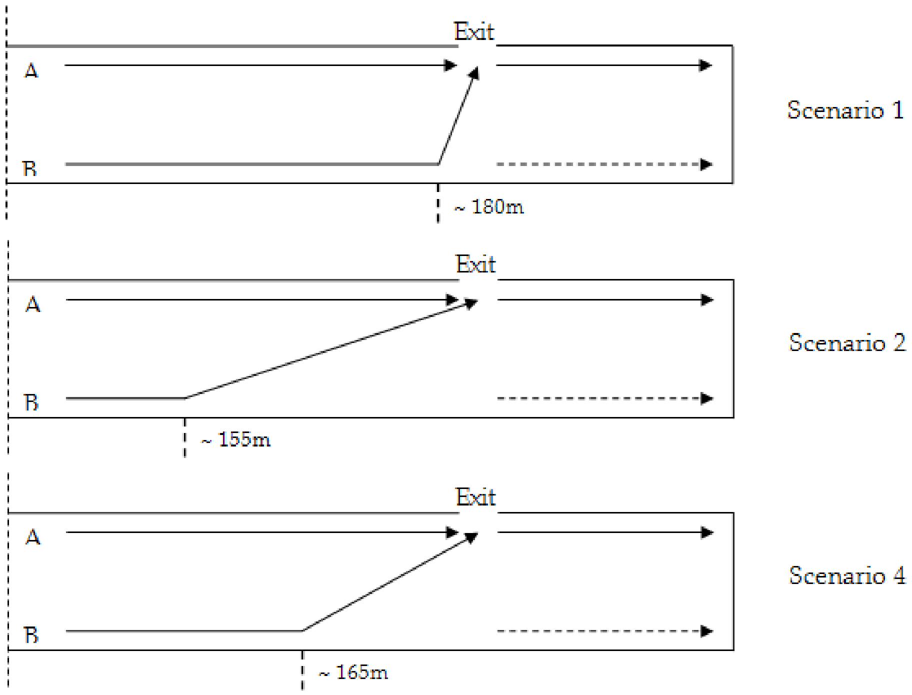


Figure 79: Walking paths produced by CRISP for Scenario 1, 2 and 4

Even though the way-finding tools do not have a significant effect on the movement speeds of the participants, their effects can be clearly seen in the movement patterns produced by the models as demonstrated in Figure 79.

The analysis revealed that the type of way-finding tool used in the model did have an effect on the movement path of the participant during the simulation. For scenario 1, the participants only moved towards the exit once they were nearly parallel to the emergency exit; whereas, for the other two scenarios the participants tended to move towards the exit much sooner within the tunnel, with participant in scenario 2 (way-finding lights) moving, on average 25m earlier than scenario 1. The pattern of movement for scenario 4 was similar to that of scenario 2 and showed that the participant started to move toward the emergency exit once they had entered the directional speakers “sound zone”, which was 15 m from the emergency exit. In addition, the results produced by the model are very similar to those produced during the experiments, with the only slight difference being that for Scenario 2 and 4 the location of the occupant’s deviation towards the other side of the tunnel happened at a similar point, whereas in the model they occurred 10 m apart.

8.2.8 Discussion and conclusions Experiment Series 2

The purpose of the experiments involved the attempt at modelling the live evacuation experiment results *A Priori* to the conduction of the experiment. Using only the cross-section plans and the standard behaviour with the modelling program (CRISP) a series of simulations were created and analysed. The initial simulation showed that walking speeds of the occupants were consistent at a value of 1.4 m/s, which is considered the average walking speed of an occupant without hindrance. The hindering effects of the smoke was recreated by altering the program’s optical density and the initial simulation showed that the walking speeds of the occupants reduced to an average of 0.9 m/s which is consistent with values produced by other researchers experiments [32].The results produced by the models were very similar to the results obtained from the evacuation experiments with the mean for the experiments being 0.92 m/s and the mean range for the simulations being 0.991 – 1.019 m/s. Unfortunately, the individual experiment walking speeds are unavailable for each type of installation used, making it difficult to compare the values, yet it can be seen that the values produced by the models were consistent with the mean value produced during the experiments.

The true effects of the installations are their ability to attract occupants towards the exit and their effectiveness is based upon the movement paths of the occupants from the side of the tunnel towards the emergency exit. In the experiments, as discussed above, the most effective was the loud speaker, followed by the flashing green lights, and finally the standard emergency exit sign. The original modelling code did not include the use of flashing lights nor loud speakers and as discussed previously, extra coding was created for this experiment. The abilities of the new code were judged upon how effective it was at demonstrating the walking paths of the occupants and if it demonstrated the movement paths similar to that of the live evacuation. The simulation results showed that the flashing green lights were slightly more effective than the loud speaker, yet at the same time both producing similar movement paths within the tunnel. The model showed that the occupants began to cross the tunnel towards the exit significantly earlier, while maintaining their movement speed during the crossing. For scenario 1 both the live and modelling data showed that the occupants during the emergency exit sign scenario would walk along the wall of the tunnel until they were nearly parallel with the emergency exit before crossing over to the other side.

8.2.9 Experiment Series 3

As with the pervious experiments, a series of *A Priori* models were created in an attempt to predict the behaviour of the occupants based upon the experiment setup within the building. Normally, *A Priori* modelling approaches do not include any prior information on the occupants' number and location within the model. However, as the number of occupants would vary between the experiments, information on the starting locations of occupants was incorporated into the models. The number of occupants that were present for experiments 1 and 2 was 49 and 42, respectively, and their starting locations can be found in Figure 80 and Figure 81.

Figure 80: Initial location of occupants in experiment 1

Figure 81: Initial location of occupants in experiment 2

The difficulty of the *A priori* modelling method is creating the human behavioural set lists that will be used to predict the occupant's behaviour. The standard evacuation plan for the buildings requires that each floor has two fire wardens, whose job is to go around the floor when the alarms are activated to make sure everyone has evacuated from the building. Hence, within the model two of the occupants were to be defined as "Wardens" where their behavioural sets would include, "warn household", "warn neighbours" and "investigate". The values for waiting and reacting for all occupants within the model were determined by the standard value set by the CRISP program (Table 53).

Action:	Mean time (sec):	Std.
Waiting	15	15
Reacting	45	15

Table 53: CRISP standard values for the waiting and reacting time

8.2.10 Code Development Experiment Series 3

The effect of the way-finding tool within the CRISP models comes down to the way the coding affects the route patterns of the occupants. Each way-finding tool, whether it be a visual or audio tool, is provided with a defined zone, entry into which acts like a trigger function. Once the occupants enter the zone near a way-finding tool, the coded information that is set within the run files for CRISP is triggered and affects the occupants egress route accordingly.

For the *A Posteriori* models each of the way-finding tools affected the occupants in the following way:

Way-finding Tool	Coding Trigger Effect
Green LEDs/Audio message AGB	Once triggered the code will set the degree of difficulty within the code for the exit to 1 (very easy) and change other exits to 4 (hard yet still available). If the exit is affected by fire the D.O.D. will remain at 5 (impossible to use) and not change to the value set by the modeller.
Red LEDs/Audio message WR	Once triggered the code will set the degree of difficulty within the code for the exit to 4 (hard yet still available) and change other exits to 1 (very easy). If another exit is affected by fire within the model the D.O.D. will remain at 5 (impossible to use) and will not change to a value at all.

Table 54: Coding Trigger Effect

8.2.11 Result Experiment Series 3

Each model was run for 10,000 iterations with each individual simulation using the Monte Carlo tool to randomise how the occupants reacted to the alarms. Shown below (Table 51) is the cumulative count of the number of iterations that fell within each evacuation time range for experiment 1 and 2, respectively. The flow rates for the modelling results were calculated by dividing the number of occupants by the total evacuation time for the floor and are also displayed below in Table 55.

There was a spread of values the flow rates and evacuation times across the iterations for both the priori and posteriori models. This is expected as the Monte Carlo controller could have altered each iteration, for example, to have the occupants either wait longer before reacting or wait until they are told to leave by the wardens. The average evacuation time and flow rate are displayed below (Figure 82 and 83).

	Average Evacuation Time (sec)	Average Flow Rate (p/s)
Experiment 1	174.0	0.298
Experiment 2	137.9	0.425

Table 55: *A Priori* CRISP model average evacuation time and flow rate

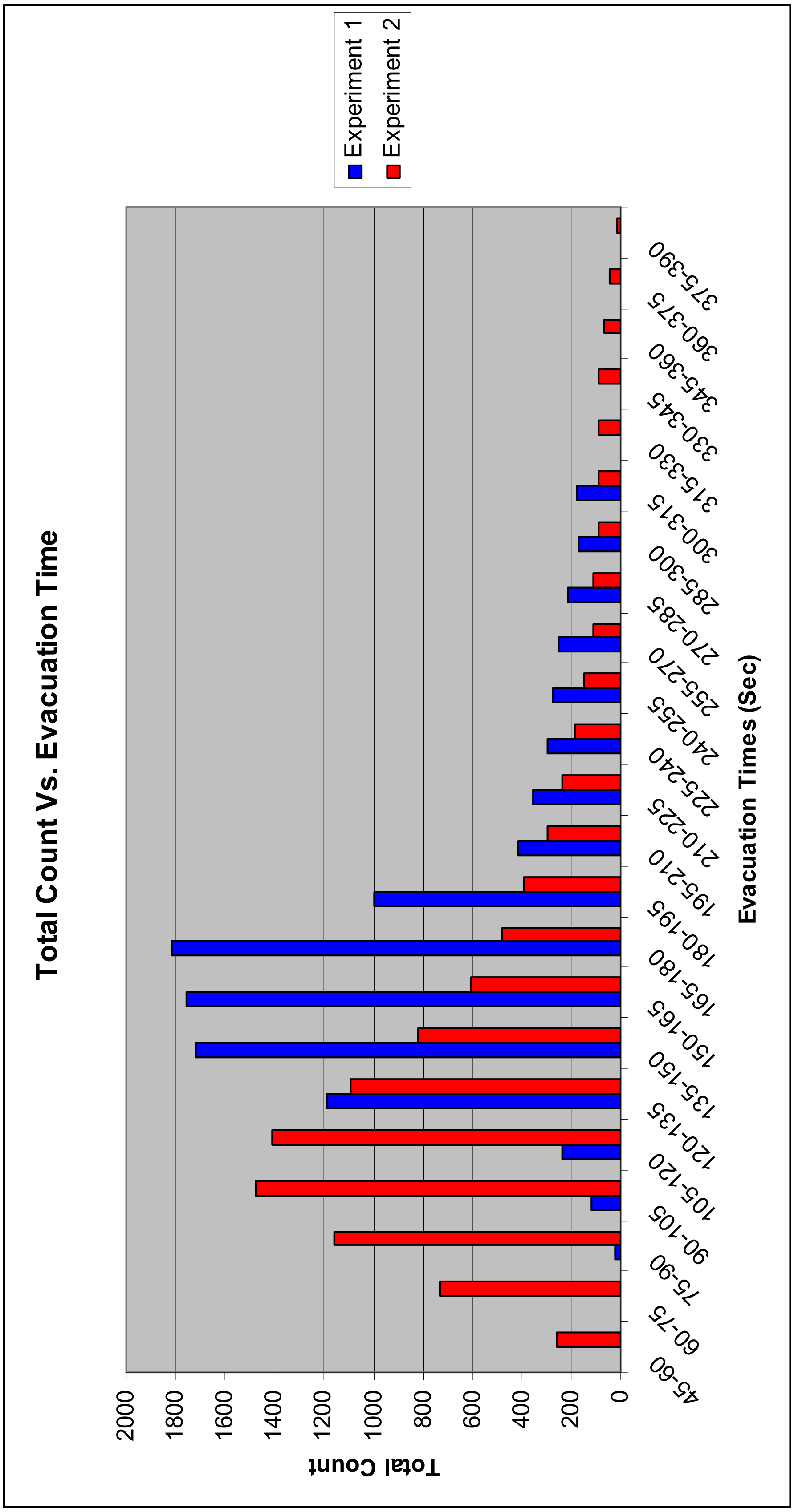


Figure 82: Evacuation time for both experiments

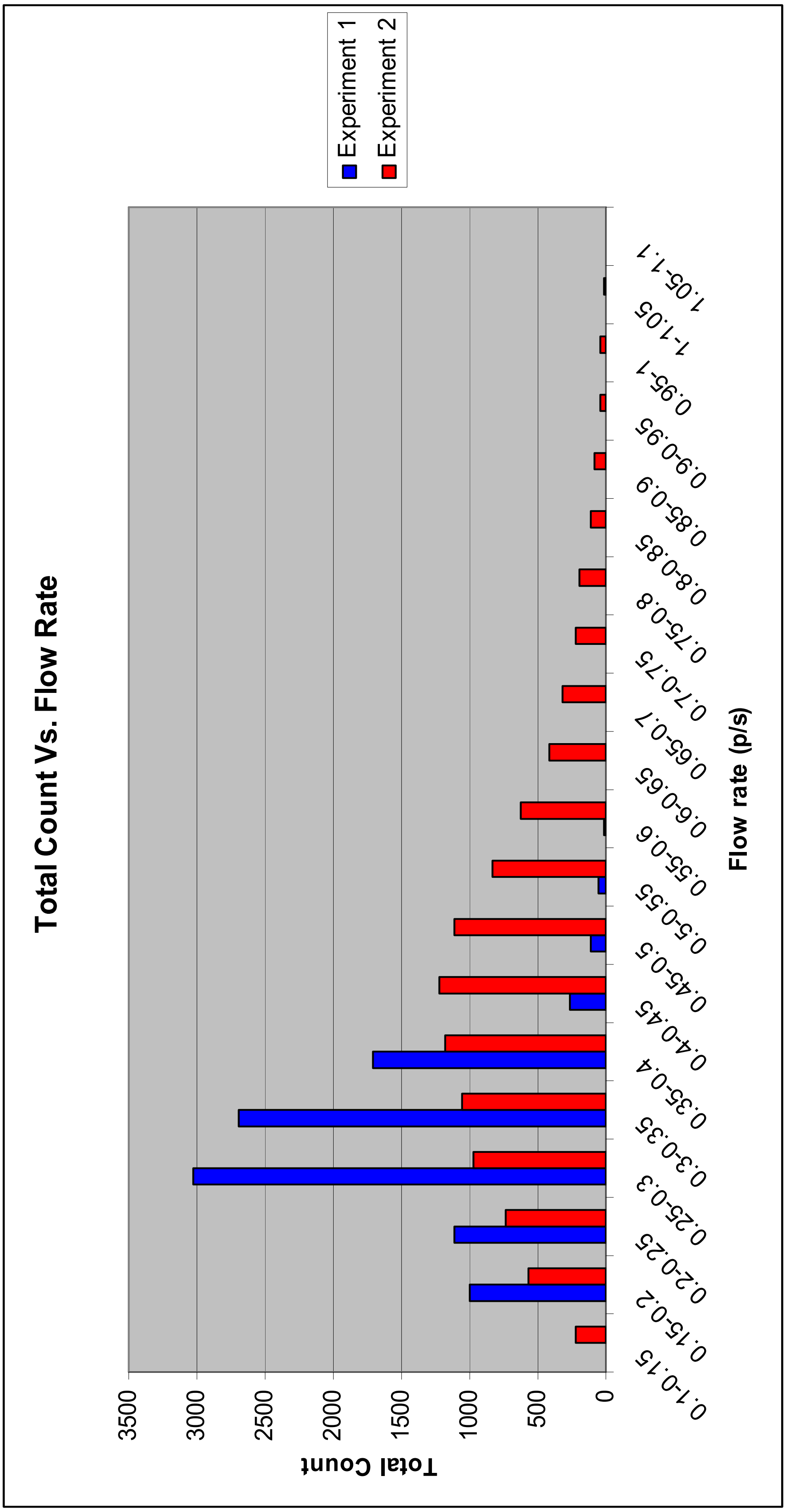


Figure 83: Flow rate for both experiments

As with the *A Priori* models, each model was run for 10,000 iterations with each individual simulation using the Monte Carlo tool to randomise how the occupants reacted to the alarms. The difference between the *A Priori* model and the *A Posteriori* models were the values used for the waiting time, reaction time and the average walking speeds of the occupants. The values used within the models are provided below within Table 56 and Table 57.

	Mean	Standard Dev
Walking Speed (m/s)	1.2	0.2
Reaction Time (s)	82	40
Waiting Time (s)	52	15
Number of Wardens: 5		

Table 56: CRISP results *A Posteriori* experiment 1

	Mean	Standard Dev
Walking Speed (m/s)	1.0	0.1
Reaction Time (s)	46	25
Waiting Time (s)	46	30
Number of wardens: 3		

Table 57: CRISP results *A Posteriori* experiment 2

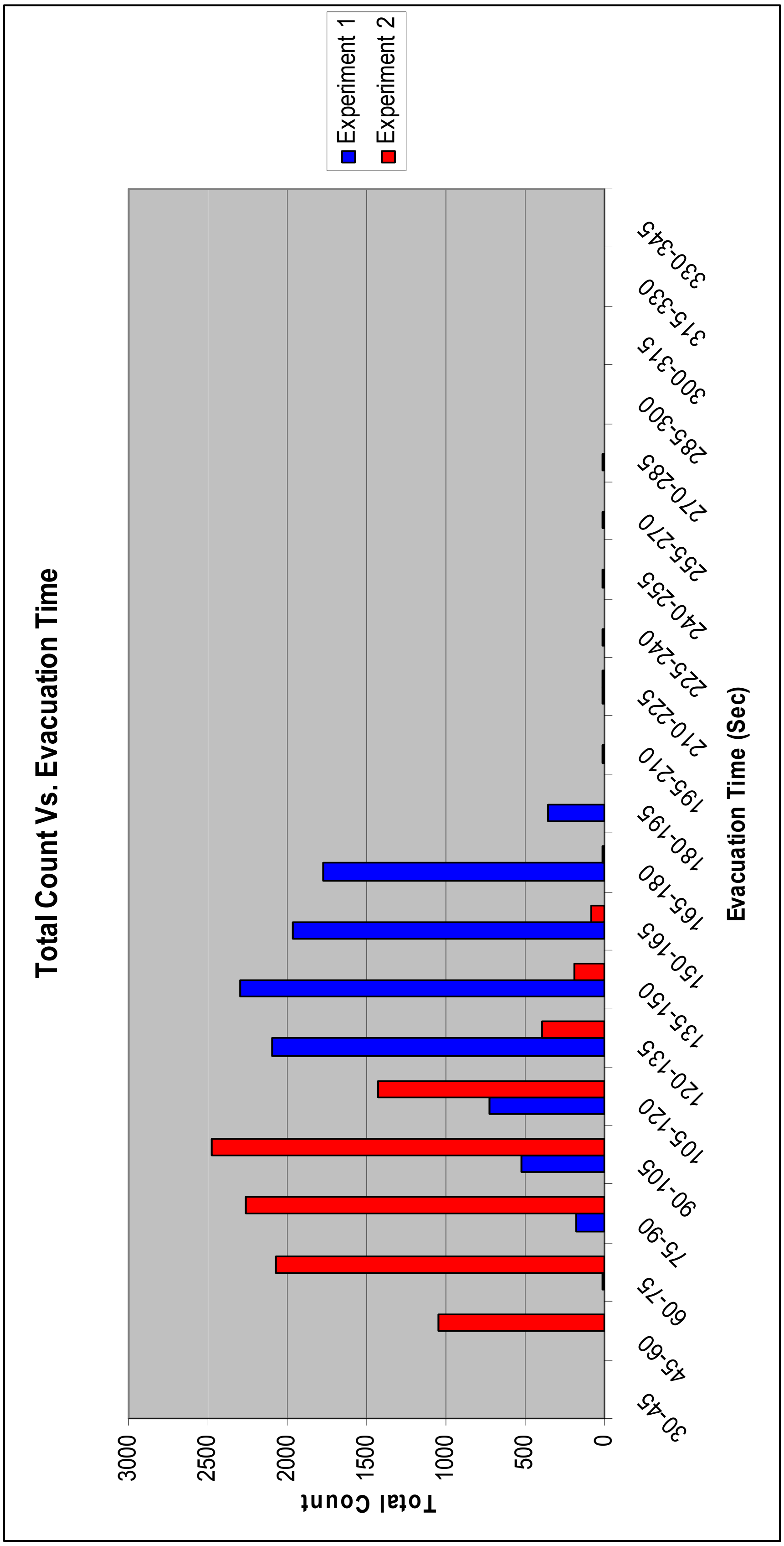


Figure 84: Evacuation time for both experiments

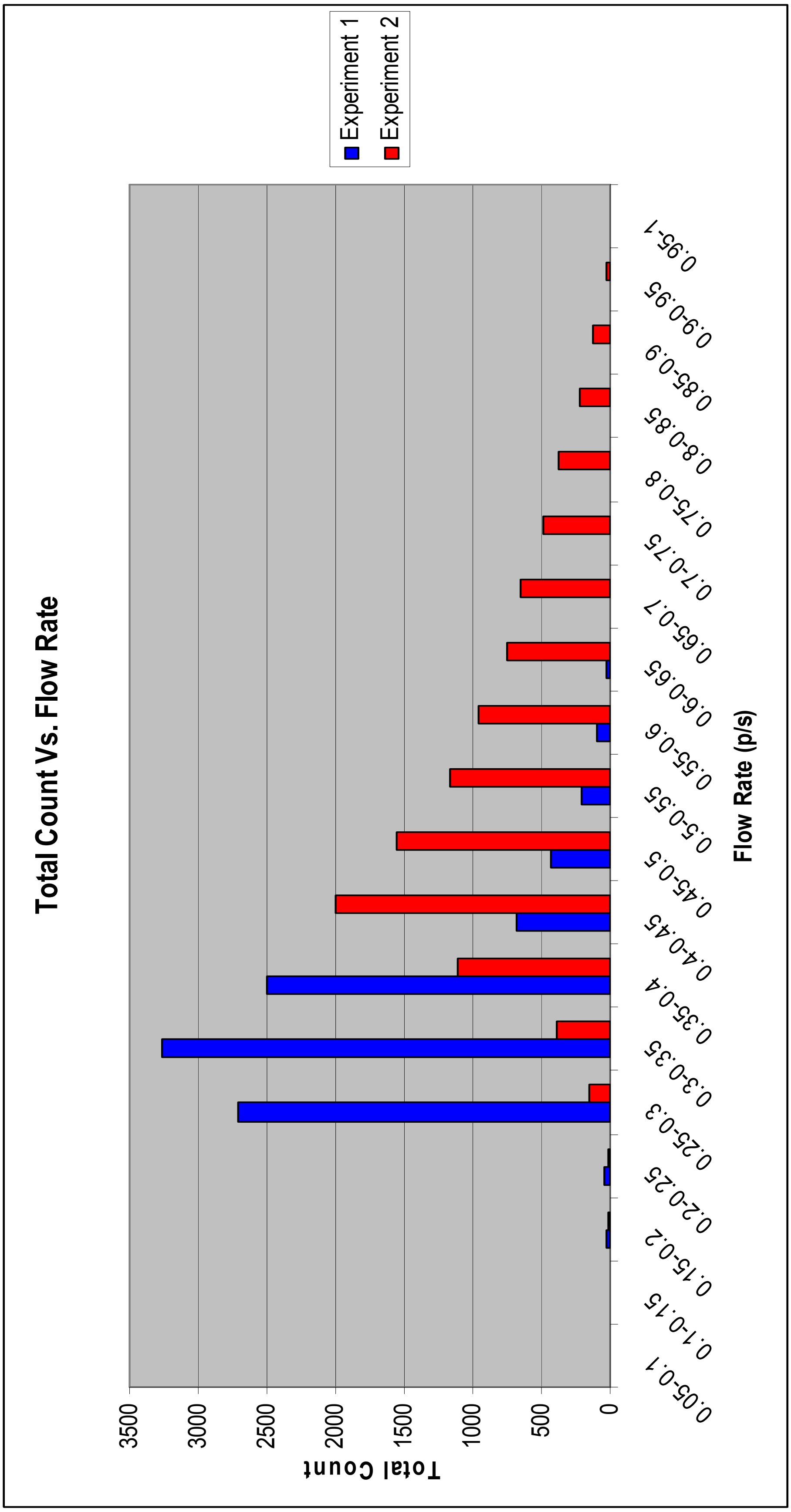


Figure 85: Flow rate for both experiments

Figure 84 shows the cumulative count of the number of iterations that fell within each evacuation time range for experiment 1 and 2, respectively. The flow rates for the modelling results were calculated by dividing the number of occupants by the total evacuation time for the floor and are displayed in Figure 85

For all the experiments there was a spread of values across the iterations for both the flow rates and evacuation times. This is expected, as the Monte Carlo controller could have altered each iteration to have the occupants either wait longer before reacting or wait until they are told to leave by the wardens. Below, in Table 58, are the average evacuation time and flow rate for the experiments.

	Average Evacuation Time (sec)	Average Flow Rate (p/s)
Experiment 1	144.22	0.344
Experiment 2	88.35	0.521

Table 58: Average evacuation time and flow rate

As stated above, an attempt at predicting the behaviour of the occupants was made for these experiments using the modelling program CRISP. The first models used unedited values for the waiting and reaction time of the occupants and the standard behavioural sets that are provided by CRISP to produce the average evacuation time and flow rate of both experiments. After the experiments were analysed the values for the waiting and reaction times were calculated and were changed within the global data input file along with new behavioural patterns that the occupants displayed. A second batch of models was run and analysed and the following results were produced.

		Experiment One	Experiment Two
Evacuation Time (sec)	*A Priori*	174.0	137.9
	Live	165	132
	A Posteriori	144.2	88.4

Flow Rate (p/s)	*A Priori*	0.298	0.425
	Live	0.300	0.318
	A Posteriori	0.344	0.521

Table 59: Comparing results for all CRISP model

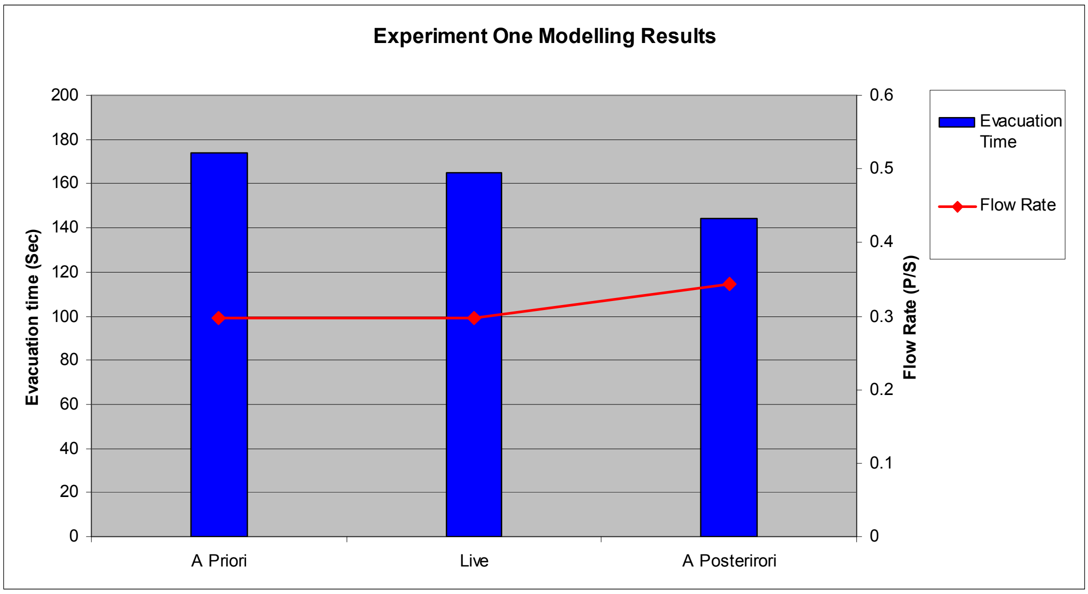


Figure 86: Experiment 1 comparing evacuation time and flow rate

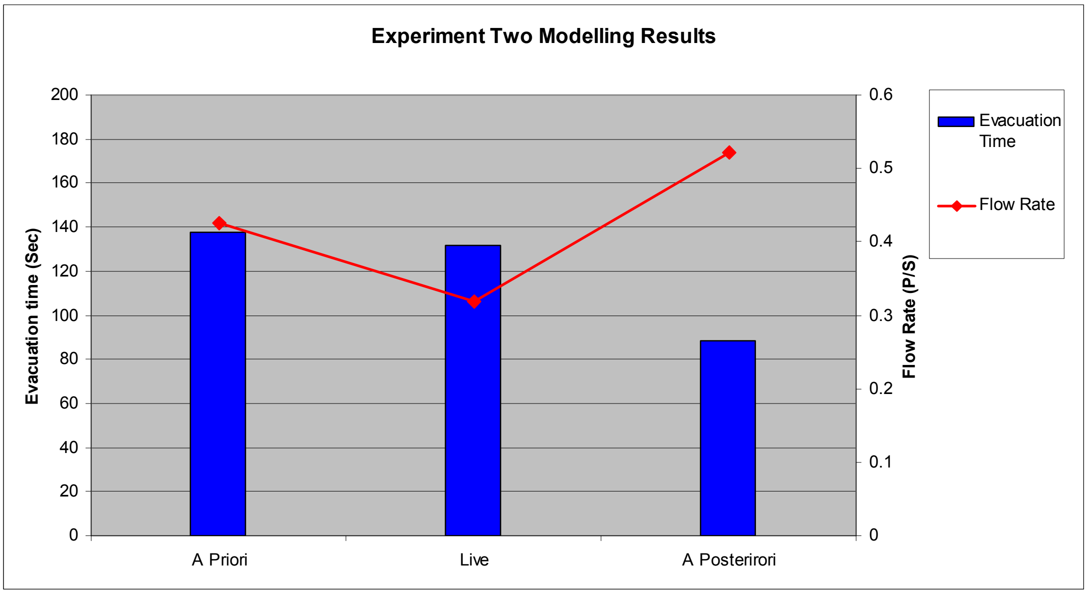


Figure 87: Experiment 2 comparing evacuation time and flow rate

The results above show that the predictive capability of CRISP varied between the two experiments. The *A Priori* model for the first experiment produced very similar values to that of the live experiment data whilst the *A Priori* for the second experiment did not produce a very similar value for the evacuation time, the predicted flow rate was significantly higher, as seen in the graphs above. The difference in the results for the *A Priori* model for the second experiment can be explained by the model's incorrect prediction of the behaviours that occurred during the live evacuation.

The models predicted that some of the occupants would take extra time to investigate the closed exit before evacuating. However, the model did not predict the behaviour where occupants would discuss the situation whilst walking. Apparently due to this behaviour, occupants were walking at a slower pace towards the exit reducing the overall flow rate of the experiment. In theory, the reduced flow rate should have produced a much higher total evacuation time for the experiment and hence the CRISP evacuation time should have been significantly quicker. On further analysis of the standard model it was clear that the standard waiting/reaction time within CRISP was significantly higher than that produced by the experiment therefore it increased the average time before the occupants began their evacuation, increasing the overall evacuation time for the model.

The purpose of the *A Posteriori* models were to determine if it would be possible to recreate the results of the live experiments by altering values for flow rate, waiting time and reaction time within the CRISP models to that produced by the experiments. However, when both models were updated to incorporate the average value for waiting and reaction time, produced from the respective experiments, both models predicted a significantly lower evacuation time which was due to a significantly higher flow rate.

Using the experimental waiting/reaction times affected the overall evacuation time of the models significantly, as predicted, producing what some may say could be considered a failure. Normally, the results produced by the model would be considered a failure if we based the pass/fail criteria on the model's ability to predict the flow rate and evacuation time of the experiment. The experiments were conducted to see the effects on the human behaviour of the occupants that occurred due to the closing off of a main exit and whether or not a person's exit choice could be influenced/changed by the installation of way-finding tools within the building.

The updated CRISP modelling program, which incorporated new coding for the use of way-finding lights and directional audio, was able to predict a similar movement path to that of the live evacuations and demonstrate how the installation of way-finding tool would affect the decisions made by the occupants, by having the occupants cross the tunnel further away from the exit than waiting till they were directly across from it.

The majority of the models showed that as occupants within the AGB seminar room corridor begin to evacuate towards the main stairwell they would stop once they were within the directional audio trigger zone and begin to head towards the other main exit within the building based on the behaviour predicted by CRISP. As the occupants head towards the other end of the simulated building they would walk into the green LED trigger, programmed into the models, near the secondary egress door and change their route to use this exit instead. Within the AGB side of the building, the occupants would head towards the main exit and once within the trigger zone, programmed into the models, of the red LED lit exit door they would stop and turn around and head to the only other available exit within this building. The occupants, who entered the directional audio trigger zone, programmed into the models, as they head towards the main exit, would change direction and headed towards the emergency exit without going near the main exit.

The behaviour demonstrated within the model is very similar to that of the occupants during the live evacuation. The only behaviour that would be difficult to predict/produce was the exchanging of information between occupants. Within the experiment the majority of occupants were able to determine the information provided by the way-finding tools, whereas within the models all occupants were able to determine the information perfectly. The occupants within the evacuation experiments were unaware of the new tools, hence the exchange of information. The efficiency of the way-finding tool will be easy to increase by providing the occupants with training concerning the tools within the building on an annual or bi-annual basis.

8.2.12 Discussion and Conclusions Experiment Series 3

The experiments conducted provided detailed data on the effect of providing a wide range of information to occupants via the use of way-finding tools, while highlighting the effect on the occupant's behaviour during an evacuation. Furthermore, the experiments demonstrated how the removal of a building main egress route could influence the movement speed, movement paths and behaviours of the occupants. It may be argued that the results cannot be applied for every possible egress situation that could occur during an evacuation of a building. However, these experiments were conducted to determine whether or not the use of way-finding tools could affect the evacuation process of the occupants who had no prior knowledge of the evacuation and the use of the way-finding tools.

The dominant behaviour present throughout the first experiment was the use of the main exits from the building while ignoring the secondary egress routes available. However, the analysis suggests that the exit choice of the occupants is also influenced by the exit choices made by others, whereas the dominant behaviour present throughout the second experiment was taking time to investigate the closure of the main exit while discussing with other occupants about the possible egress routes still available.

The main purpose of the experiments was to test whether it is possible to influence an occupant's exit choice, using way-finding tools, when the preferred route was unusable. Of the types of visual tools tested the green LEDs were found to be the most effective at providing information to the occupants, while the red LEDs initially confused the occupants and took extra time to decipher. Of the types of audio tools tested, the speaker providing information on the location of an available exit was better received and understood than the speaker providing information on the closure of an exit, which occupants took to be that the final building exit was closed, not the exits upon the level.

The experiments tested how the different way-finding tools would work within a simple building environment yet it is unknown how they would work within a more complex situation, for example a shopping centre. The audio tools may be more effective as an installation within a building with a large number of people with the lights being provided as a secondary evacuation tool, as discussed within Chapter 3 audio cues are better received and interpreted by occupants compared to visual cues. On the other hand, the visual tools may be more efficient within a situation where the audio tools may be contaminated by other audio sources or may be affected by reverberation/acoustic echoing.

The purpose of this experiment was to examine the ability of way-finding tools and how they can be used to influence the final exit choice of occupants when the preferred mean of escape is removed without prior warning. This experiment was also used to test the predicative capabilities of the new way-finding tools coded into CRISP in order to be used to test the feasibility of a sensor-linked system as an egress solution that incorporates the requirements of the design codes and the nature of the human decision-making process. The following section will use CRISP to model an evacuation from a high-rise building in order to test the feasibility of using a sensor-linked system to facilitate an efficient evacuation from a variety of possible evacuation scenarios.

8.3 Demonstration via Feasibility Study

In order to determine whether or not the proposed sensor-linked system is a viable option/tool to use during an emergency evacuation, ideally a large scale test involving the required sensors, K-CRISP and the network of computers required to run the program predictive simulation ability would be conducted. However, due to budget required and the amount time needed to organise the experiment it was not be a feasible operation within the scope of the current project. The experiments that were used to validate the original CRISP program were part of a nationwide experiment that took years of effort and a significant cost to undertake [52]. As the earlier experiments were a success and CRISP was able to perform as expected it meant that the program would have potential to be used to predict the fire development within a building and map the approximate location of the current fire/smoke and the occupants while running the way-finding systems.

The live experiments conducted for this thesis were conducted to provide a data set on how people behave during different evacuation scenarios while studying the effects of different way-finding tools on their decision-making processes. The experiments were also used to develop the CRISP code to incorporate the new way-finding tool and the behaviours that could occur during their usage.

The following chapter of this thesis will therefore include a feasibility case study of an existing office/retail building, located in Auckland, New Zealand, which will demonstrate, through CRISP modelling, how it is intended that the system would work and cope through various emergency scenarios.

Before conducting the feasibility study it is important to determine the criteria that will be used to validate if the results produced by the models are considered successful. For the scenarios investigated within this chapter it will be the influence the system has on the occupants' movements and its ability to guide them away from a dangerous situation that will be considered as part of the success criteria.

However it should be noted that the simulation will not be able to completely model the complexities of the true behaviours of the occupants in a real life evacuation, no model program to date has ever been considered to have this ability. However, the study will be able to demonstrate the effects of queuing caused by the re-distribution of the occupants to other routes while portraying potential issues occupants may have with the technology.

8.3.1 Britomart east building

The Britomart East Office and Retail building is part of larger complex that was part of a larger project aimed at revitalising the ports near downtown Auckland. The projects consisted of nine new buildings to be used as retail, office and food/beverages locations for the City. The entire fire safety engineering design for the project was awarded to Holmes Fire and used alternative design solutions and the New Zealand Building Code to create the egress solutions for each building. Hence, for this feasibility study the Britomart East Building was chosen as it combined the use of evacuation zones and four egress stairs as part of the alternative design in order to provide a safe means of escape for the occupants. The building is on twelve levels that are predominantly used as office space. It is located above the underground Britomart Train Station and provides some retail space at ground level.

The building is made up of three main portions; East 1, East 2 and East 3. East 1 and East 2 are predominantly office floors that extend from Ground to Level 9 inclusive. The Ground level provides retail space to the streets frontages on three sides, loading dock and plant space, the entry foyers and lobbies for the office levels above, and fire separated access/ egress for the train station below. The fourth side of the building is frontage to Takutai Square (public space). Level 1 – 9 of East 1 and East 2 are designed for office use and are separated by an atrium space, which is covered at approximately the height of Level 10 and has permanently open louvers at high level along the north and south faces of the atrium. The upper floor levels in the portion of the building known as East 3 (Levels 10 to 12) are positioned at the eastern end of the building, and are also designed for office use. These levels are also provided with separate fire safety systems.

Occupants on the ground floor can either evacuate the building via the main entrance to each retail shop to the public footpaths or through the atrium area directly to the outside. Levels 1 to 9 of the office space are provided with four stairs that have been designed for evacuation during a fire. East 1 and East 2 are considered as two separate evacuation zones which are provided with stairwells (Stair 2 and 3) and common stairwells (Stair 1 and 4) that were designed to be used by both zones. East 3 on levels 10 – 12 are provided with access to Stair 2, 3 and 4.

The New Zealand Building Code requires the building to be provided with an automatic fire sprinkler system with smoke detectors and manual call points. The design also provides a voice communication system, smoke control in the air handling system, pressurisation of safe paths, fire service lift controls, emergency lighting in exitways, a fire hydrant system and a fire system centre.

The egress width for the building was based on the maximum occupant load on an individual floor, which is on level 3, according to the design. The levels were divided into East 1 and East 2 and were considered separated buildings, meaning the fire alarm systems were also separate, allowing for independent evacuation. The occupant loads for East 1 and East 2 were determined to be 164 and 170 occupants per floor respectively. The egress widths were designed to allow each zone to be evacuated either separately or at the same time (although this is not intended as the first response). Below in Table 60 is the occupant design load for the building based on the numbers used within the design data for the project.

Floor	Use	Occupant Load
Level 02 (office)	East 1	158
	East 2	163
Level 03 (office)	East 1	167
	East 2	170
Level 04 (office)	East 1	163
	East 2	166
Level 05 (office)	East 1	163
	East 2	166
Level 06 (office)	East 1	160
	East 2	163
Level 07 (office)	East 1	160
	East 2	163
Level 08 (office)	East 1	152
	East 2	156
Level 09 (office)	East 1	122
	East 2	128
Level 10 (office)	East 3	125
Level 11 (office)	East 3	97
Level 12 (office)	East 3	84

Table 60: Design occupant loads for Britomart East

Using the architectural drawings, the design notes and occupant loads stated within the Holmes Fire report, a model of the building was constructed within CRISP to be used as part of the feasibility study.

The purpose of the feasibility study is to investigate the effects the system will have on the occupant's movements and exit choices as they evacuate the building. As the development of the way-finding tools used within the simulations was based on the experiments conducted with Chapters 7.4-7.6 the results will also be analysed to determine if the assumptions made about how the occupants will interact with the tools are valid. The study will also be conducted to investigate how occupants exit choices, based on the information provided by system, can affect the queuing times, evacuation time and flow rates of occupants and if it can lead to the failure of the egress design solution developed using prescriptive design codes.

The way-finding tools used within the models will be a combination of the audio and visual tools developed as part of the live experiments (see Chapter 7 for more details). Visual tools will be "installed" on both sides of the emergency exits used to access the stairwells and audio tools will be installed above the exits, on both sides of building and within a section of each of the stairwells on each level to avoid audio contamination between the two messages within close proximity. Audio tools were also installed on every mid floor landing within the model to also avoid audio contamination between two messages, (i.e. those near the exits).

8.3.2 CRISP Feasibility Study.

As stated within Chapter 5, the modelling program that will be used by the intelligent egress system will be CRISP which was chosen based on its performance for the Dalmarnock fire tests [56] and the FireGrid final demonstrator D7.4 [12].

In order to test the feasibility of the intelligent egress system a series of different scenarios will be tested within the Britomart East Building. These models will look into the effects of varying the location of the fire/smoke within building on the evacuation of the occupants, the flow rate, evacuation time and queuing based on if the system is present or not. In order to compare the effectiveness of the intelligent egress system each fire scenario will be modelled twice, once without the use of the way-finding system and the other using the way-finding tools to simulate how the system would work in a real life application.

Shown in Table 61 is the list of scenarios that will be modelled as part of the feasibility study. It should be noted that the scenarios chosen are "worst case" and are highly unlike to occur within the building in reality.

Scenario	Description
1	Base Case: False Alarm (evacuation without the presence of smoke/fire)
2	Egress Stair 2 unavailable
3	Egress Stairs 2 and 3 filled with smoke between levels 2 - 8
4	Common Stairs 1 and 4 filled with smoke between levels 2 - 8

Table 61: Model Scenarios

The design of the model was based upon the original floor plans of building, which have changed since the completion of this thesis. Due to the design of the CRISP interface and its use of zone modelling the floor plan used within the model was simplified compared to the actual design, as shown in Figure 88:

Actual building floor plan, versus Figure 89: CRISP model building floor plan, as it would allow for a more robust model with less scope for errors to occur due to geometric anomalies and contour inconsistencies.

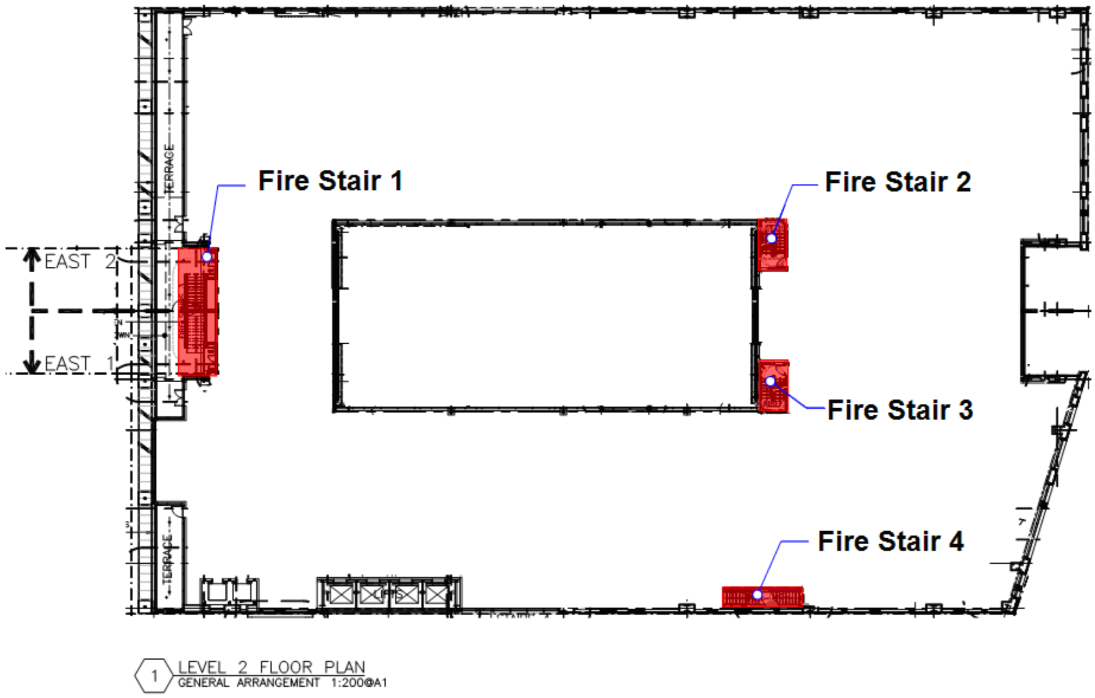


Figure 88: Actual building floor plan

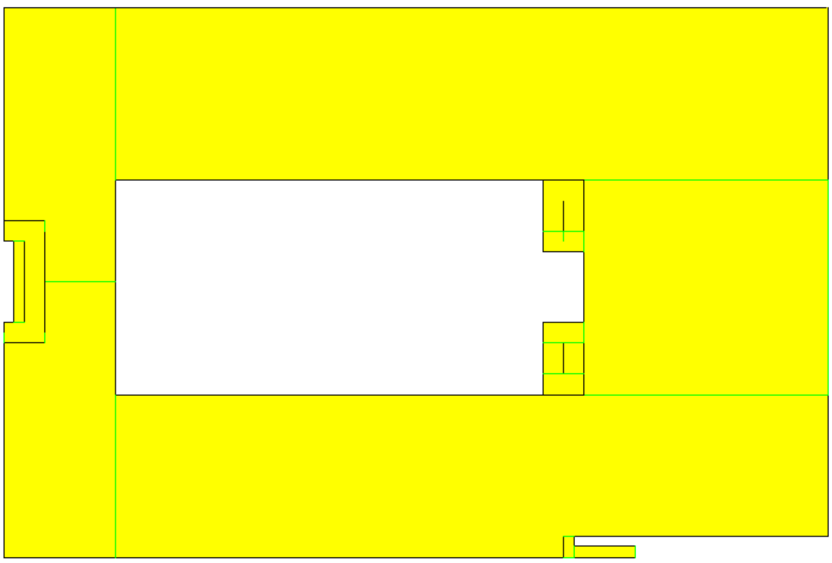


Figure 89: CRISP model building floor plan

The behavioural model incorporated all the information gathered during the experiments discussed in Chapters 5, 6 and 7 and included the coding developed for the use of different way-finding tools. The initial set up of the systems within the building to aid evacuation included the use of exit signage and an automatic alarm system with smoke detectors, manual call points and sounders installed throughout each level. As stated above, the building is comprised of office and retail areas, for the study only the office areas were modelled as the occupants within the retail areas are not required to use any of the stairwells to evacuate the building during an emergency.

An example of the Monte Carlo randomising process is demonstrated in Figure 90, showing even before the model is run that the location of the occupants within each floor will vary from case to case. This randomising process is a key feature of CRISP modelling that will facilitate its use as part of the feasibility study.

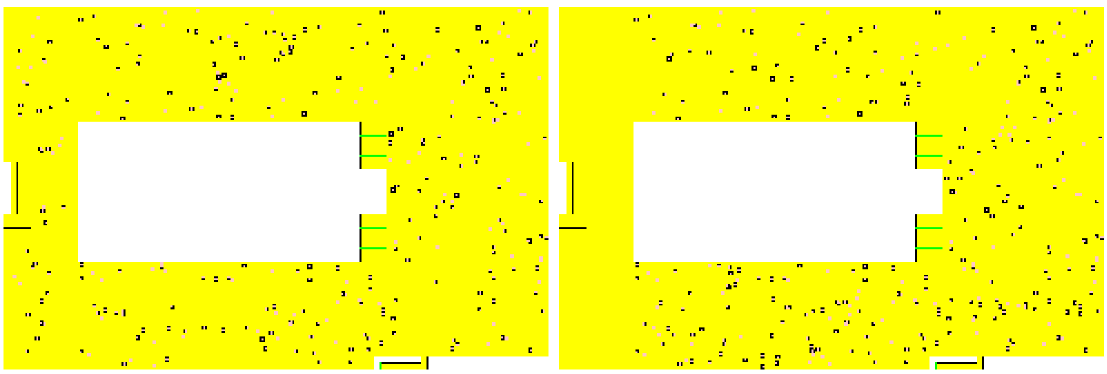


Figure 90: Example of the Monte Carlo Process

There was difficulty in constructing the CRISP model due to the lack of user-friendly interfaces and the sheer size of the building itself. As the program uses .dat input files created within notepad a small error can take significant amount of time to correct. The majority of issues came about due to the fact that CRISP is a zone model which works more effectively the more square and simple the geometry. Hence, each level was simplified and constructed using a series of rectangles with interconnecting full height open vents. This came about as initially all the levels were modelled as a single room causing the zone model to fail during the contour creating stage of the simulation due to their complex shape.

The complexity of the creating each stairwell within the building also led to computational errors in running the simulation due to user issues during the writing of the geometry files. It was not until the simulation of scenario 3 that the geometry issues within stairs 2 and 4 were discovered, due to vent locations, which meant all previous simulations had to be discarded and remodelled leading to lengthy time delays. Initially, the re-modelling of scenario 3, where the use of the intelligent system led to longer delays than without was the system considered to be another modelling failure. However, after running a few simulations it appeared that this result was producing positive results and the delay was due to queuing effects and not due to a failure of the model.

8.3.3 Scenario modelling overview

The raw data produced by the models for each scenario will be used to determine the average evacuation time (sec), the flow rate (p/s) and the number of occupants who used each stairwell during their evacuation. As CRISP utilises a Monte Carlo tool to randomise the location and the behaviour of the occupants the models for each scenario were run for 100 iterations in order to produce a wide range of data for the analyses. It should be noted that the flow rate determined for each scenario was taken as an average flow rate for the entire building, i.e. they were calculated by dividing the number of occupants located within the building by the total evacuation time, instead of per stairwell as the occupants, during some scenarios, chose to move to another stairwell due to queuing and the movement of the fire/smoke.

The first stage of the feasibility study was to determine a base scenario that could be used to compare the influence of the system and how the removal of an egress route can affect the occupant's decisions during an evacuation.

8.3.4 Scenario 1

In order to determine the feasibility of the intelligent egress system a base case scenario was needed. In this case, the base case scenario was considered to be a "trial evacuation" from the building as all stairwells were available and clear of fire/smoke. The evacuation times and flow rate for the occupants within Scenario 1 are displayed below in Figure 91 and Figure 92. It should be noted that the term "total count" refers to the number of scenarios that had evacuation times within the range provided before, with the same of these columns adding up to 100.

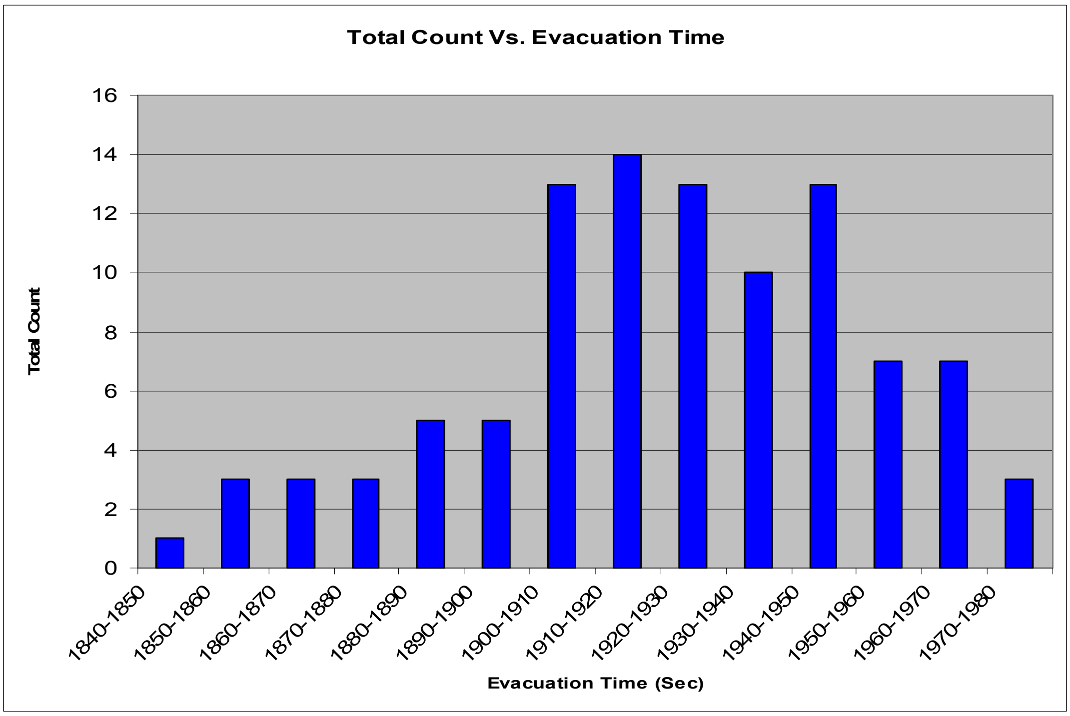


Figure 91: Total Count vs. Evacuation Time Scenario 1

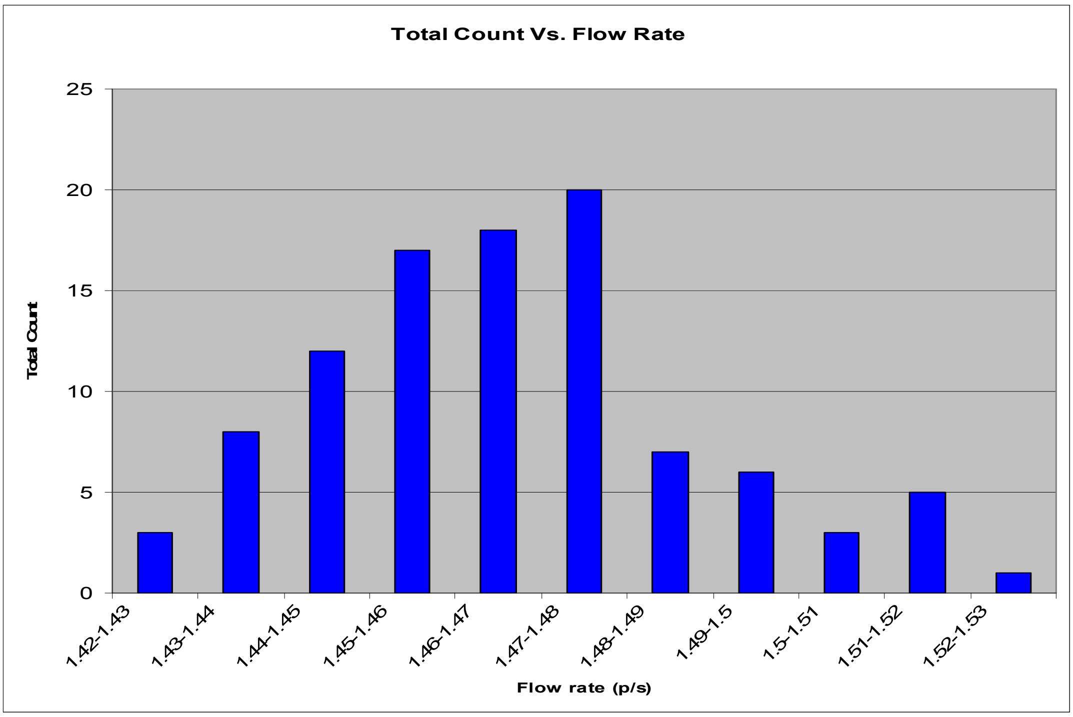


Figure 92: Total Count vs. Flow Rate Scenario 1

The average evacuation time and flow rate are displayed below in Table 62.

	Average Evacuation Time (sec)	Average Flow Rate (p/s)
Scenario 1	1920.9	1.47

Table 62: Scenario 1 CRISP average evacuation time and flow rate

Even though the evacuation time and flow rate is a significant factor in determining the efficiency of an egress design, for the feasibility study the most important factor is the choice of exit made by the occupant. The goal of the system is to have the ability to influence the occupants exit choice and help guide them towards a safer egress option during an evacuation. However, as the system was not used as the base case within this scenario this model was conducted to see what exit was preferred by the occupants and whether queuing at the entrance to the specific stair influenced the occupants' egress choices, shown in Figure 93-Figure 96.

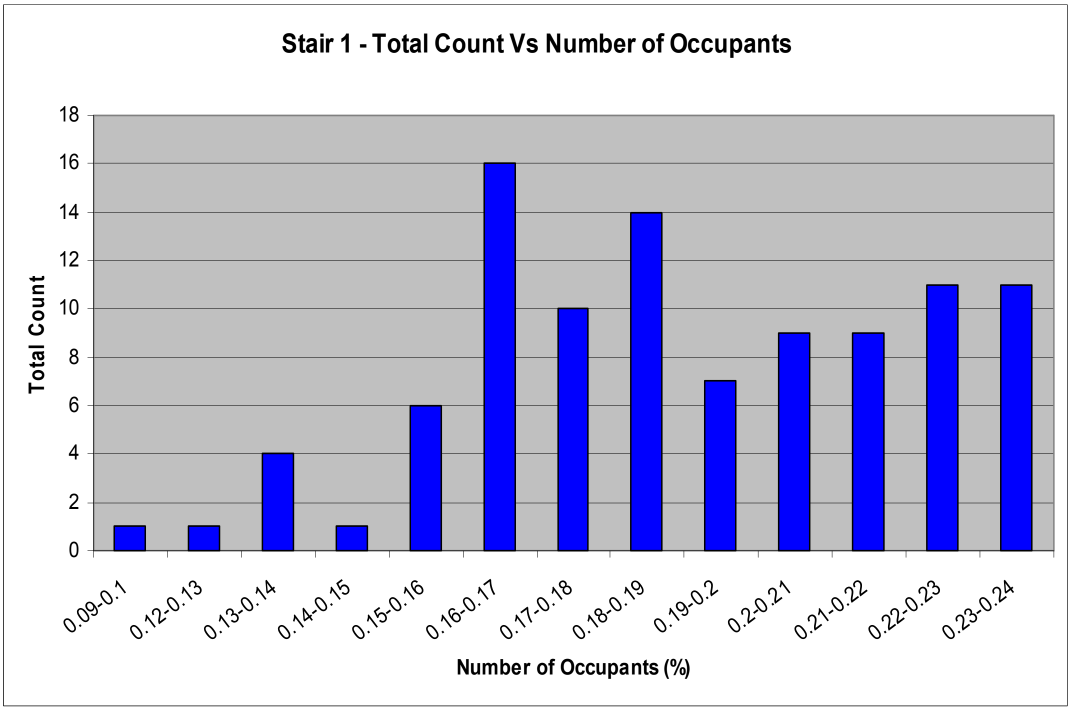


Figure 93: Stair 1 - Total Count Vs Number of Occupants

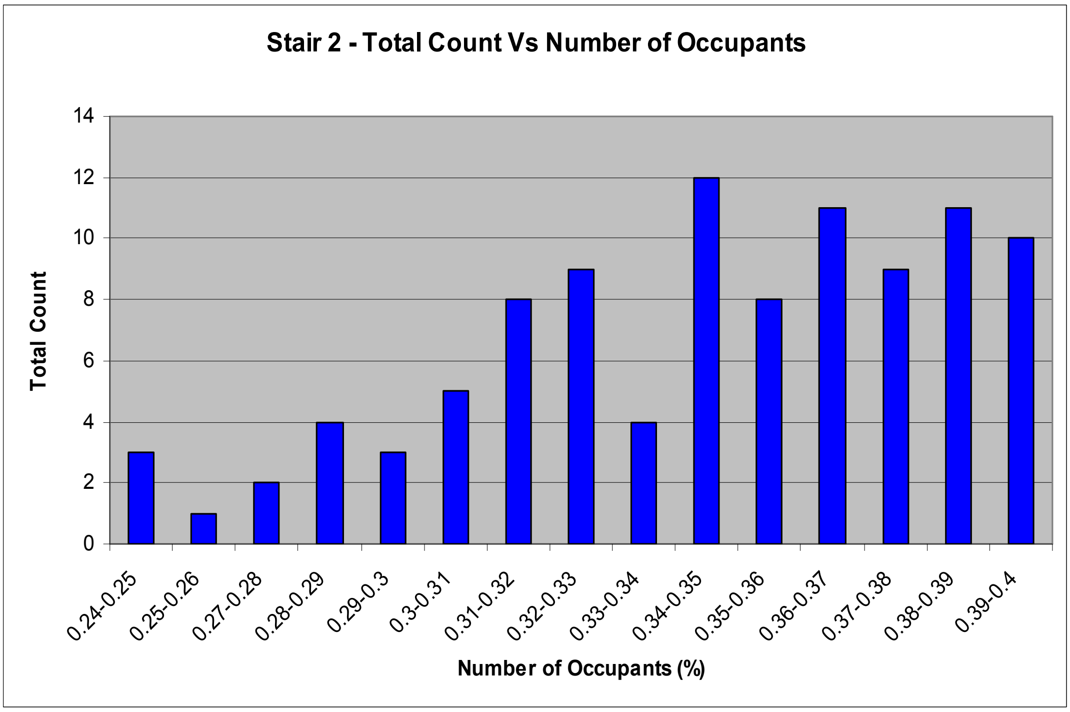


Figure 94: Stair 2 - Total Count Vs Number of Occupants

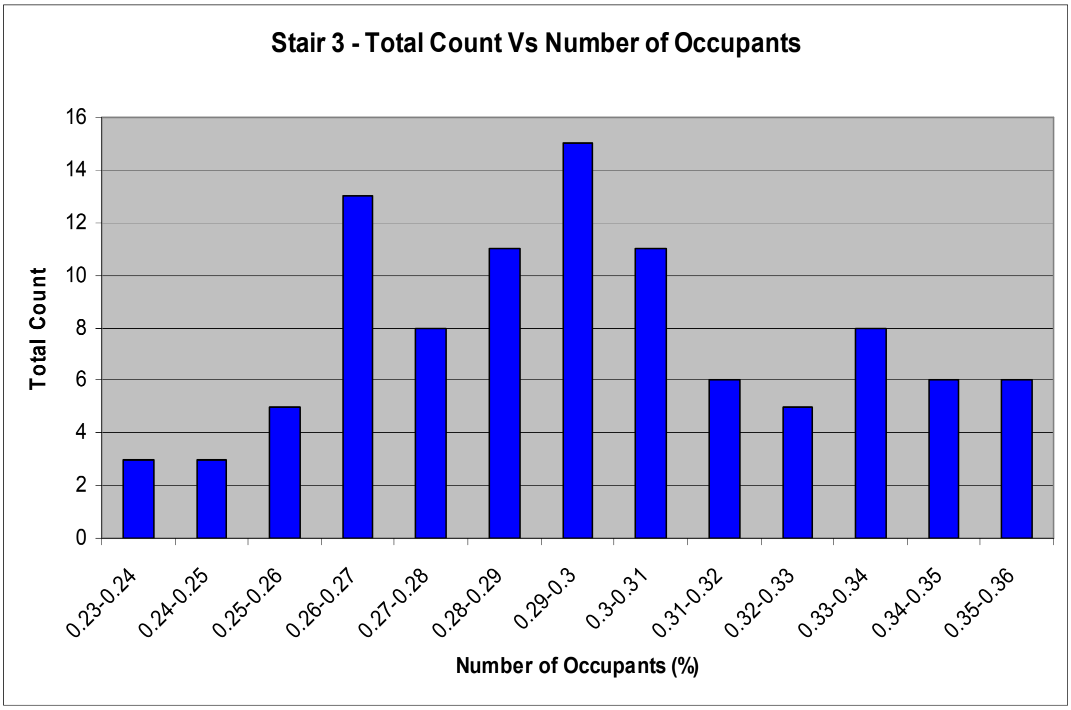


Figure 95: Stair 3 - Total Count Vs Number of Occupants

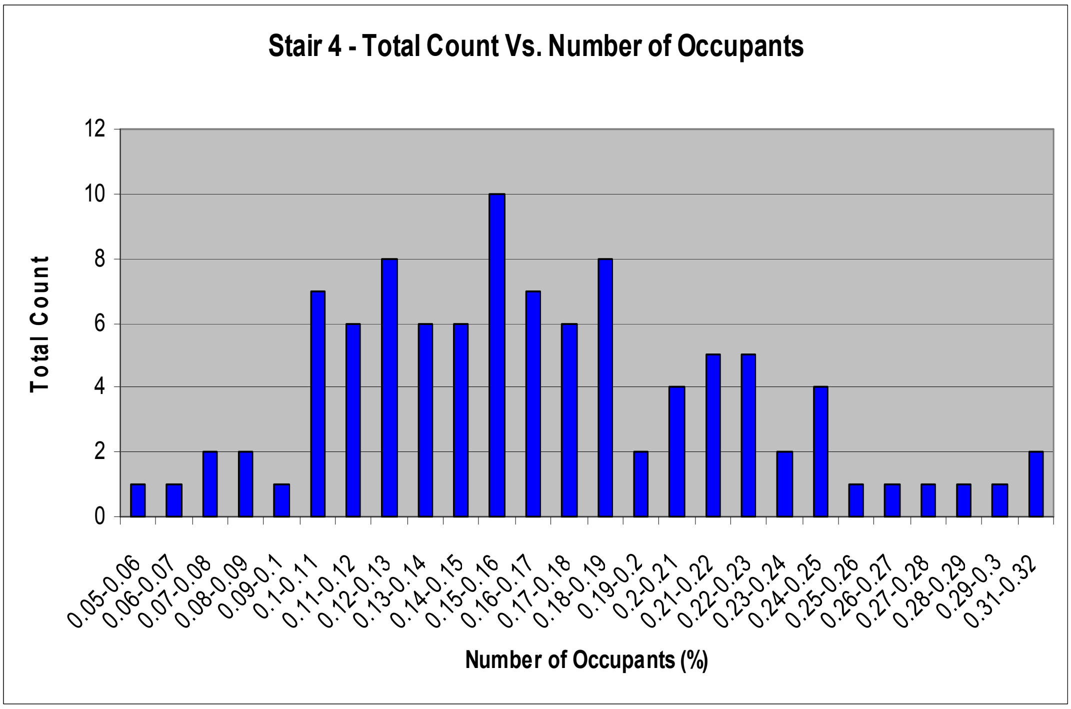


Figure 96: Stair 4 - Total Count Vs Number of Occupants

For each stairwell the flow rate and evacuation time again showed a spread of values across the iterations, as expected. The average number of occupants and the percentage that used each stairwell is shown in Table 63

	Average Number of Occupants	Average Percentage
Stair 1	476	19.1%
Stair 2	862	34.5%
Stair 3	740	29.6%
Stair 4	418	16.8%

Table 63: Scenario 1 CRISP average number of occupants per stairwell

It can be seen from the results in Table 63 that the preferred stairwell for evacuation of the building was Stair 2, located North East corner of the building, closely followed by Stair 3, located in the South East corner. These two stairwells are designated as purpose built egress stairs for the building and are designed to accommodate higher occupant loads by having increased door and stair widths.

As seen during the analysis of the simulated evacuation the occupants first head towards the egress stairs (Stairs 2 and 3) before deciding to use the next closet exit due to the queuing encountered at these stairs (As shown in Figure 97). With the base case scenario results determined the next step is to model each Scenario within Table 61 and cross-examine the feasibility of the system.

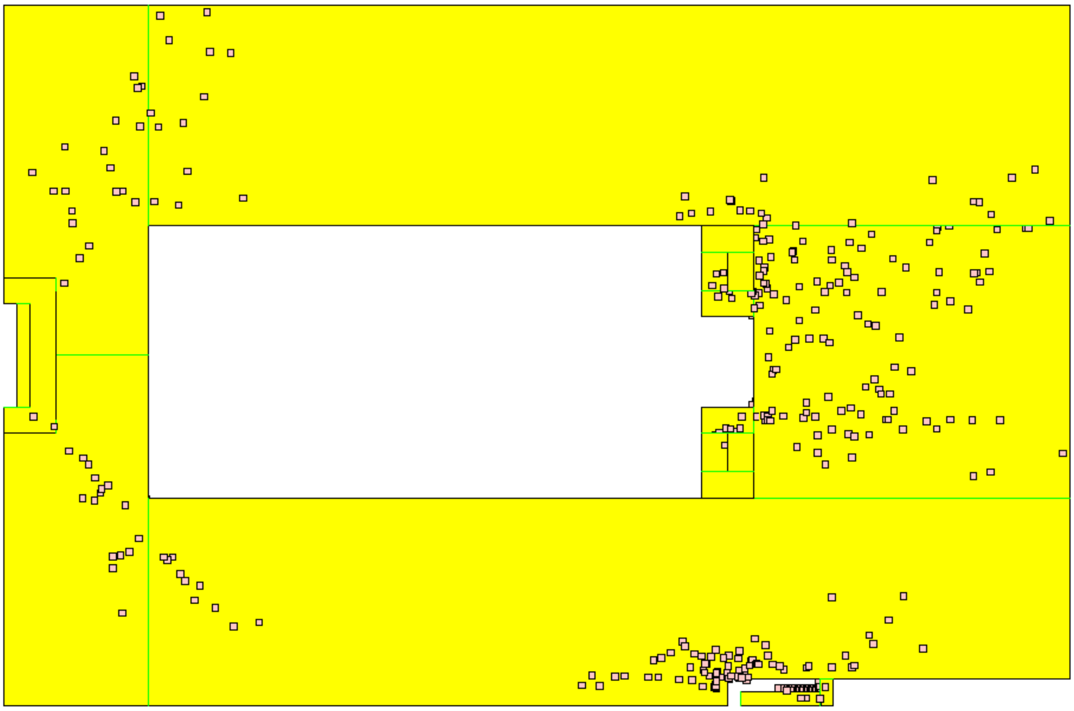


Figure 97: Exit Choice and Queuing Location for Scenario 1 - Level 7 (~120 second.)

8.3.5 Scenario 2

The first scenario tested as part of the feasibility study simulated the case where one of the four stairwells was filled with smoke making it nearly impossible to be used during an evacuation. The stair chosen for the scenario was one of the two purposely designed egress stairs known as Stair 2. The stairwell was designed with wider doors and stairs, as well as larger landings than Stair 1 and 4, which are used as everyday stairs. As with Scenario 1, the evacuation times and flow rates for the occupants within Scenario 2 are displayed in Figure 98 and Figure 99.

Scenario 2	Average Evacuation Time (sec)	Average Flow Rate (p/s)
With System	1981.7	1.42
Without System	2055.4	1.37

Table 64: Scenario 2 CRISP average evacuation time and flow rate

As can be seen within Table 64 the average evacuation time and flow rate was quicker for the simulation where the system was installed within the building. This indicates that the system had an influence on the evacuation behaviours and exit choice of the occupants. However, the goal of the system is to influence the exit choice of the occupant based on the availability of the egress routes within the building. The ideal situation would be to see little to no queuing at the entrance doors into Stair 2 during the entire simulation. It is expected that some occupants may begin to use the stairwell in the simulation without the system before they reach the smoke and have to exit the stair and change exit routes. Hence, for each model run the number of occupants who initially used each stair was counted (based on a total of 2496), shown in Figure 100-Figure 103.

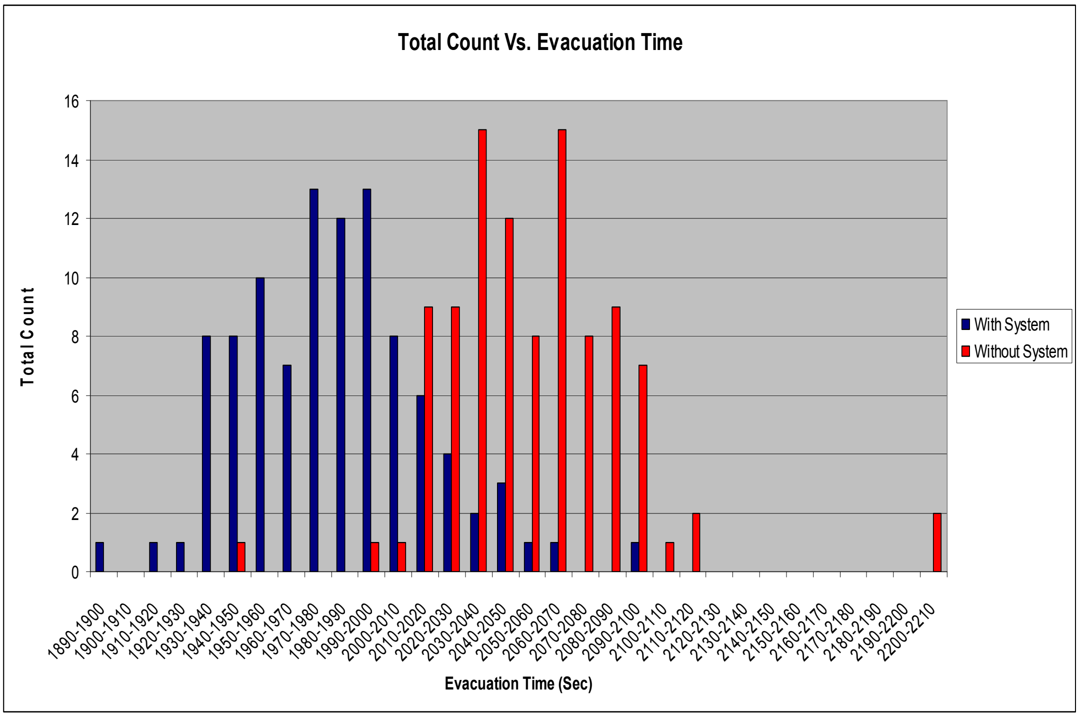


Figure 98: Total Count vs. Evacuation Time Scenario 2 with and without system

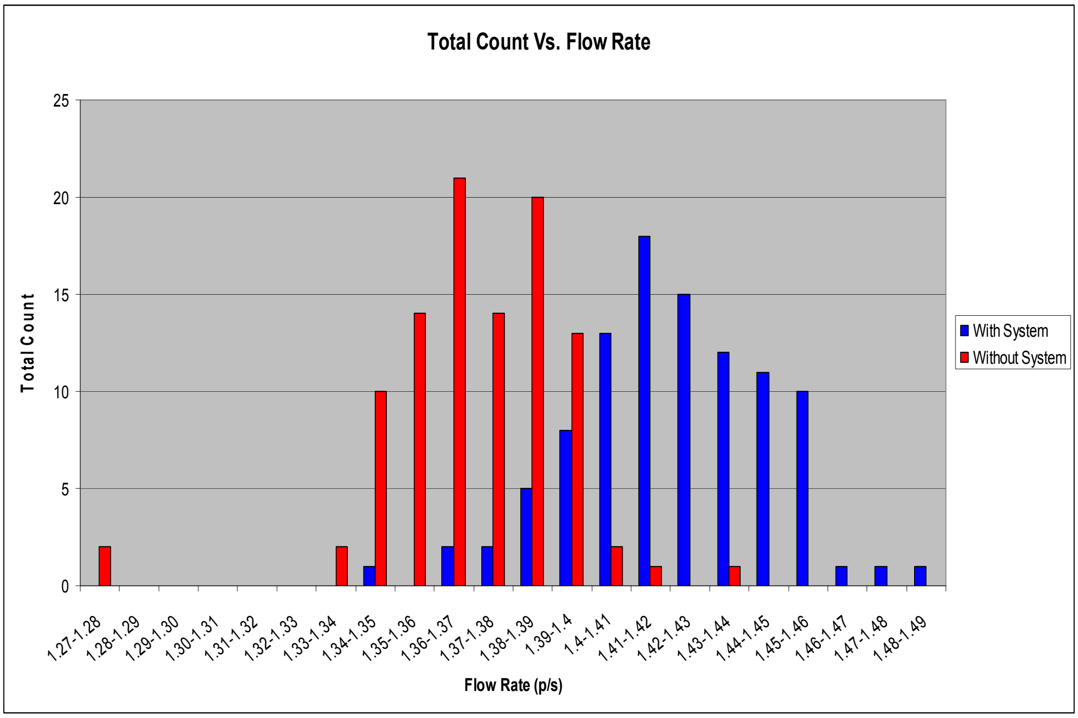


Figure 99: Total Count vs. Flow Rate Scenario 2 with and without system

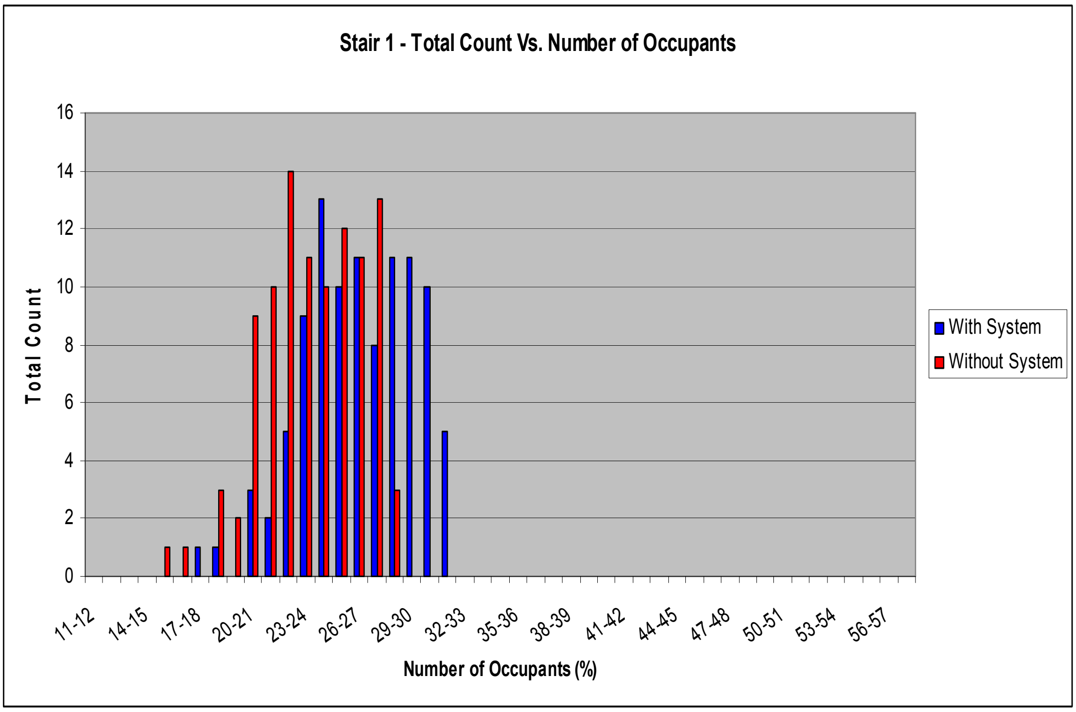


Figure 100: Stair 1 with and without System - Total Count Vs Number of Occupants

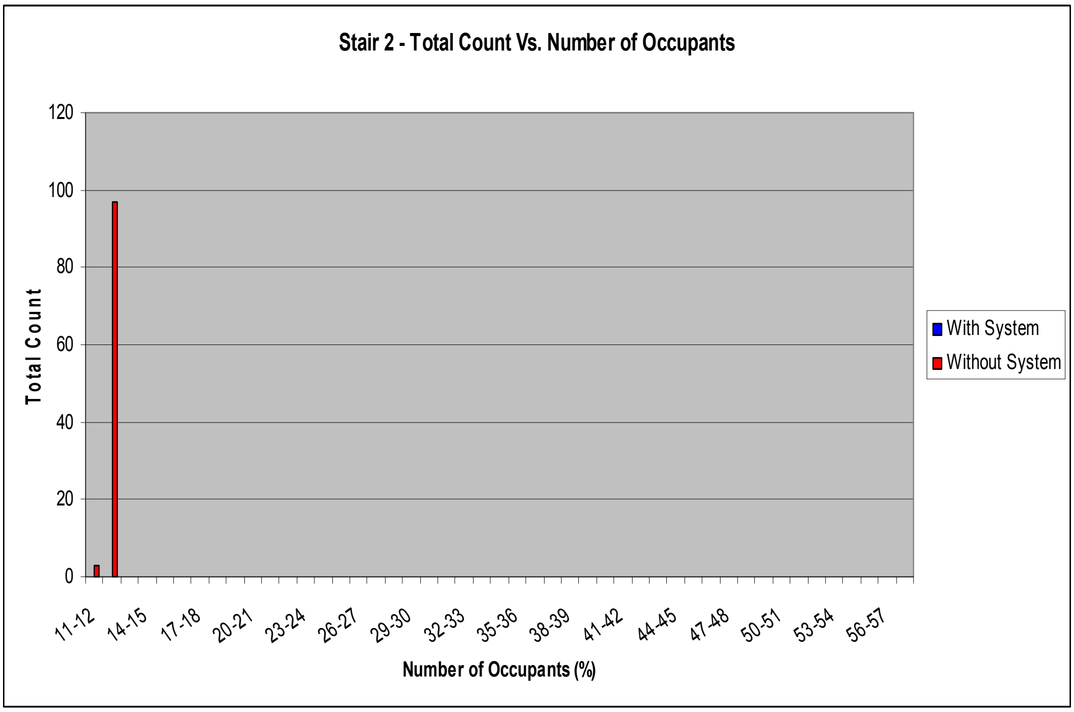


Figure 101: Stair 2 with and without System- Total Count Vs Number of Occupants

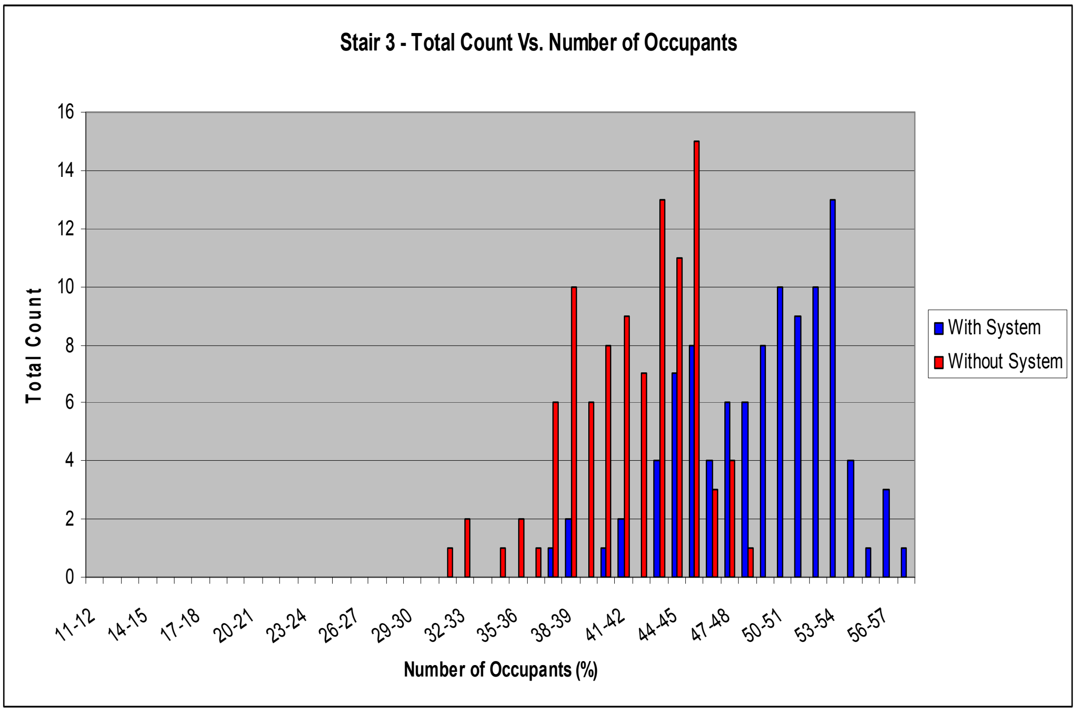


Figure 102: Stair 3 with and without System - Total Count Vs Number of Occupants

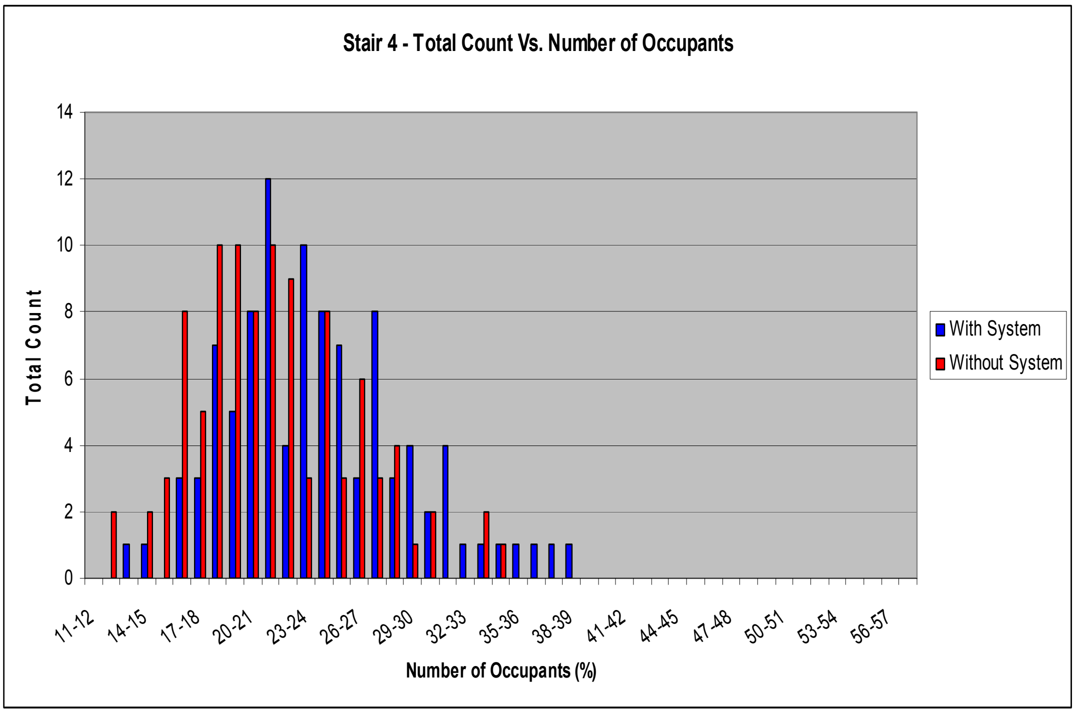


Figure 103: Stair 4 with without System- Total Count Vs Number of Occupants

It can be seen from the results in Table 65 that the system was able to direct occupants away from using Stair 2 with the majority of the occupants choosing to use the other egress stairwell Stair 3 as well as an increased used of the other everyday stairwells, as seen in Figure 104. In the simulation without the system occupants on levels 8 and above started to use Stair 2 before it was overcome by smoke at which time they choose to exit the stairwell and use either Stair 3, if the queue was small, or nearest other stair, as seen in Figure 105. Stair 1 was not favoured as an alternative route initially as the travel distance is significantly larger than the distance between the other stairs, occupants choose this alternative exit only when the queues were higher than 40 occupants at the other stairs (a fact determined by the Monte-Carlo controller).

Figure 104: Exit Choice and Queuing Location for Scenario 2 - Level 7 with System (~120 Seconds)

Figure 105: Exit Choice and Queuing Location for Scenario 2 - Level 7 without System (~120 Seconds)

	Average Number of Occupants		Average Percentage	
	With System	Without System	With System	Without System
Stair 1	661	595	26.5%	23.8%
Stair 2	0	311	0.0%	12.5%
Stair 3	1231	1047	49.3%	41.9%
Stair 4	603	543	24.2%	21.8%

Table 65: Scenario 2 CRISP average number of occupants per stairwell

8.3.6 Scenario 3

The next scenario tested was to look into the effects of having both egress stairs filled with smoke between levels 2 and 8 of the building, as these levels had the highest occupant loads within the building hence affect more peoples behaviours and decisions. This scenario was developed based on the behaviours of the occupants witnessed within Scenario 2, which includes, the high use of the egress stairwell Stair 3 and the movement of occupants from Stair 2 to another stairwell during the simulations without the use of the intelligent system. This scenario will have the intelligent system relying on the use of the everyday stairwells, Stairs 1 and 4, which were not designed to take high occupant loads compared to the egress stairwell to be used as the only egress solution for the evacuation. As with Scenario 1, the evacuation times and flow rate for the occupants within Scenario 3 are displayed below in Figure 106 and Figure 107.

Even though the building with the system installed has larger evacuation times and a lower flow rates than that the building without the system, it is its ability to direct occupants away from danger that is key for the primary purpose/use of the intelligent system. The results indicate that the Stair 2 and 3 were still used initially during the evacuation for the simulations without the system and therefore allowed for more occupants to evacuate through the everyday stairs, reducing queuing, before the occupants within Stairs 2 and 3 had to abandon their current egress route and select another.

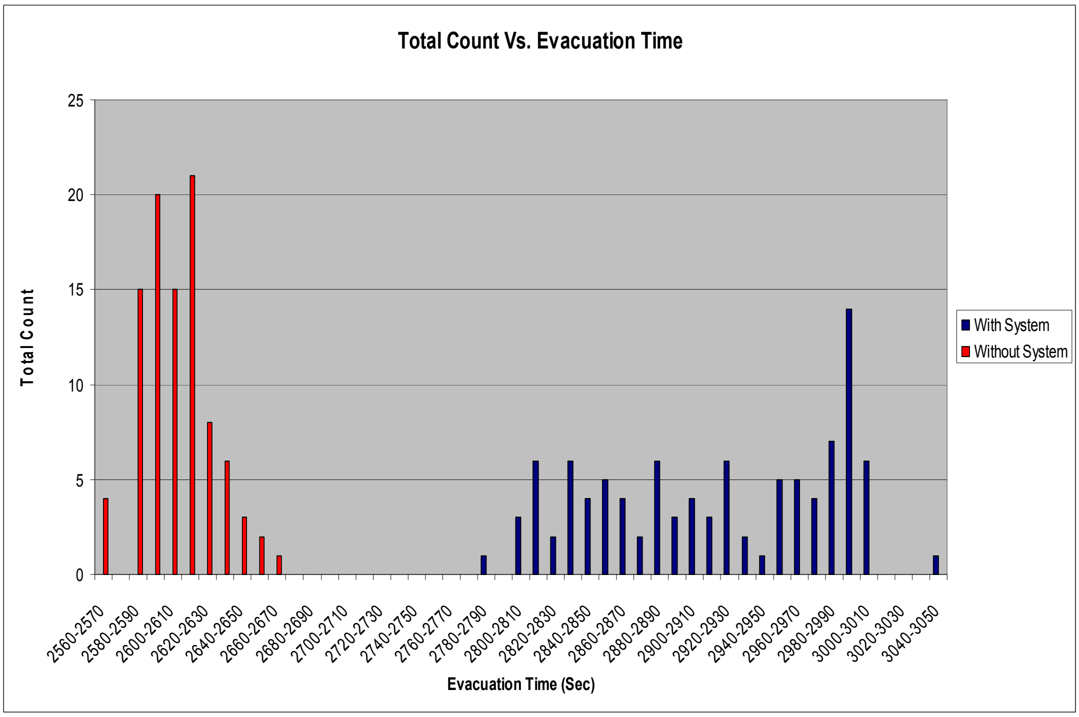


Figure 106: Total Count vs. Evacuation Time Scenario 3 with and without system

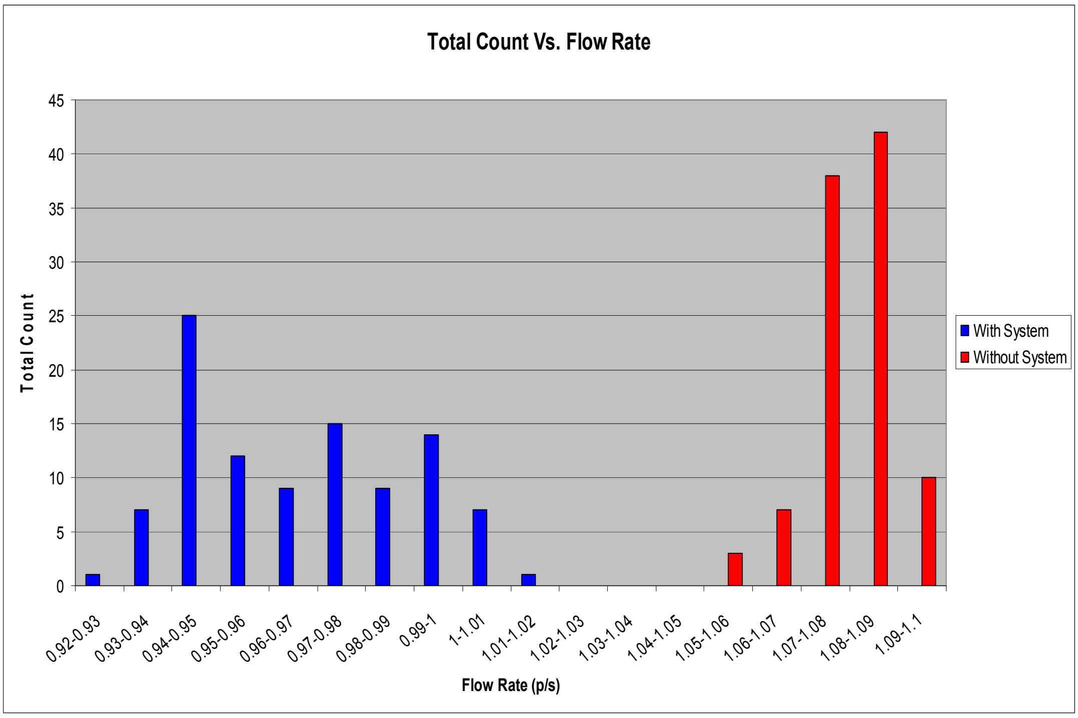


Figure 107: Total Count vs. Flow Rate Scenario 3 with and without system

As can be seen from Table 66 the average evacuation time and flow rate was quicker for the simulation where the system was not installed within the building. This is an unexpected result caused, in this specific case, by the effects of queuing experienced by the occupants at the everyday stairs within the initial stages of the evacuation as these stairs were not designed to be used by such high occupant's loads. However, it should be stated that the inclusion of the system will not always produce lower result and could be depended on other variables such as the validity of the information provided, the capacity of routes, the population distribution, etc. In the scenario with the system installed the occupants were provided with information that directed them all towards the everyday stairs on all floors which reduced the flow rate into and within the stairs significantly. The scenario without the system with the occupants upon the floors above the affected stairwells used all four stairs in the initial stages of the evacuation until they reached the smoke on level 8 before deciding to find another route. Even though this still caused queuing at the other stairs, it reduced the overall queuing time due to there being fewer occupants using these stairs in the initial stages of the evacuation, leading to a faster flow rate. The initial exit choices of the occupants during the evacuation are shown in Figure 108.

Scenario 3	Average Evacuation Time (sec)	Average Flow Rate (p/s)
With System	2917.0	0.97
Without System	2607.3	1.08

Table 66: Scenario 2 CRISP average evacuation time and flow rate

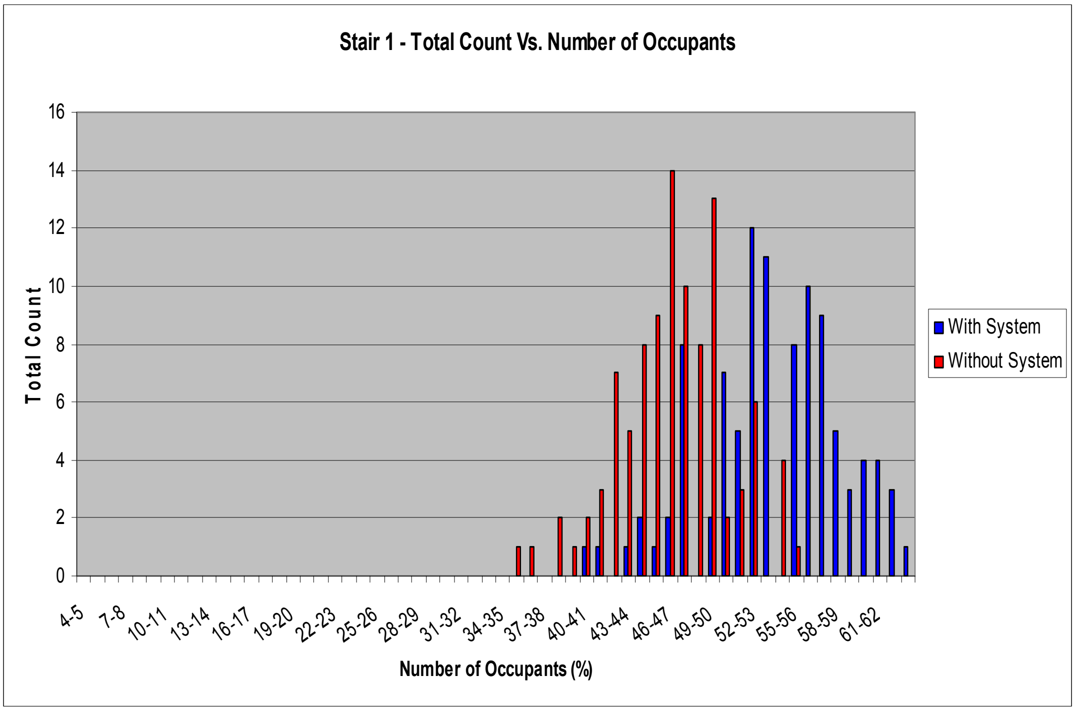


Figure 108: Stair 1 with and without System - Total Count Vs Number of Occupants

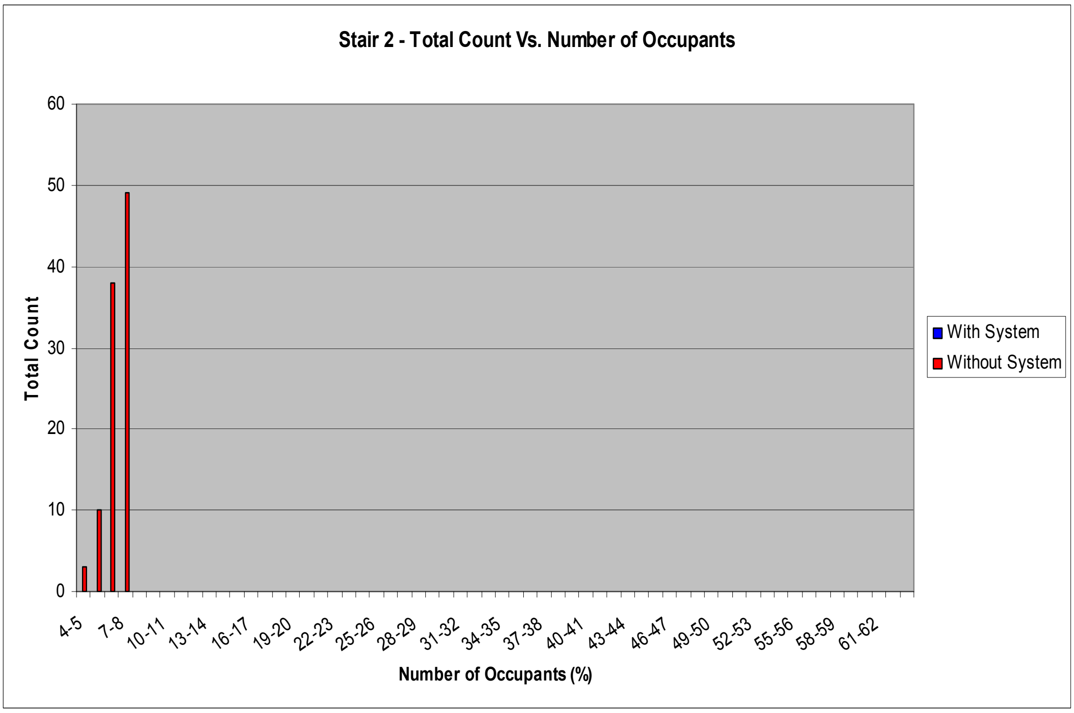


Figure 109: Stair 2 with and without System- Total Count Vs Number of Occupants

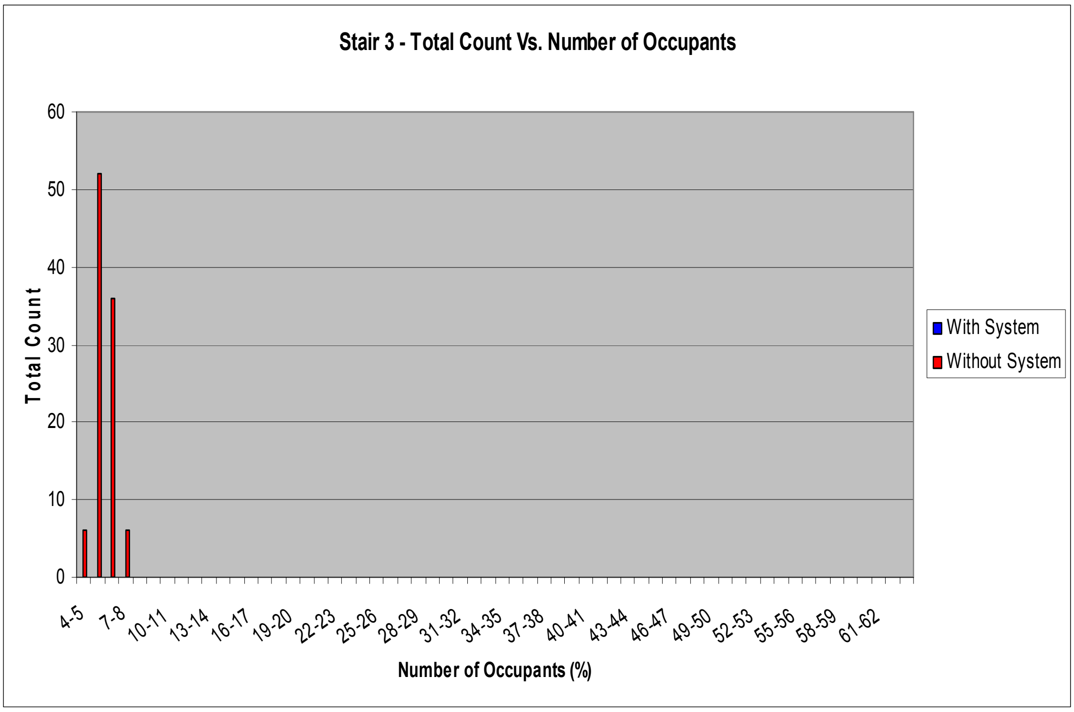


Figure 110: Stair 3 with and without System - Total Count Vs Number of Occupants

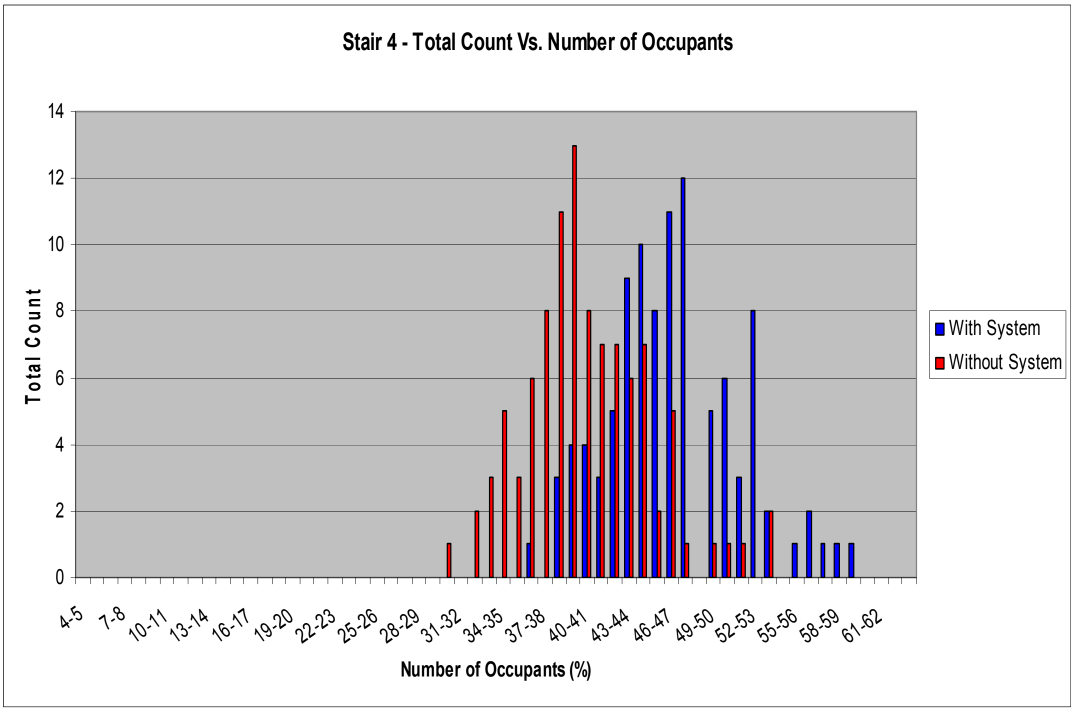


Figure 111: Stair 4 with System- Total Count Vs Number of Occupants

It can be seen from the results in Table 67 that the system was able to direct occupants away from using both Stairs 2 and 3 with the majority of the occupants splitting almost evenly between the two other available stairwells. Occupants who were on levels 10 to 12 chose to use Stairs 2 and 3 until they reached the smoke within the stairwell at level 8, where the density of the smoke was at its greatest preventing movement, and then deciding to use one of the other stairwells, as seen in Figure 113. By the time these occupants had changed stairwells the queues at Stairs 1 and 4 has decreased enough to allow a fast flow rate to occur along these egress routes. As seen in Figure 112, occupants walked past the affected stairwells and headed towards the nearest available exit to evacuate the building based on the information provided by the system. Even though the system successfully directed the occupants away from Stairs 2 and 3 it led to larger queues at the entrances for the other stairwells, hence longer evacuation times. Also as Stairs 1 and 4 were not designed as egress stairs, the increased occupant load significantly reduced both the vertical and horizontal egress flow rates.

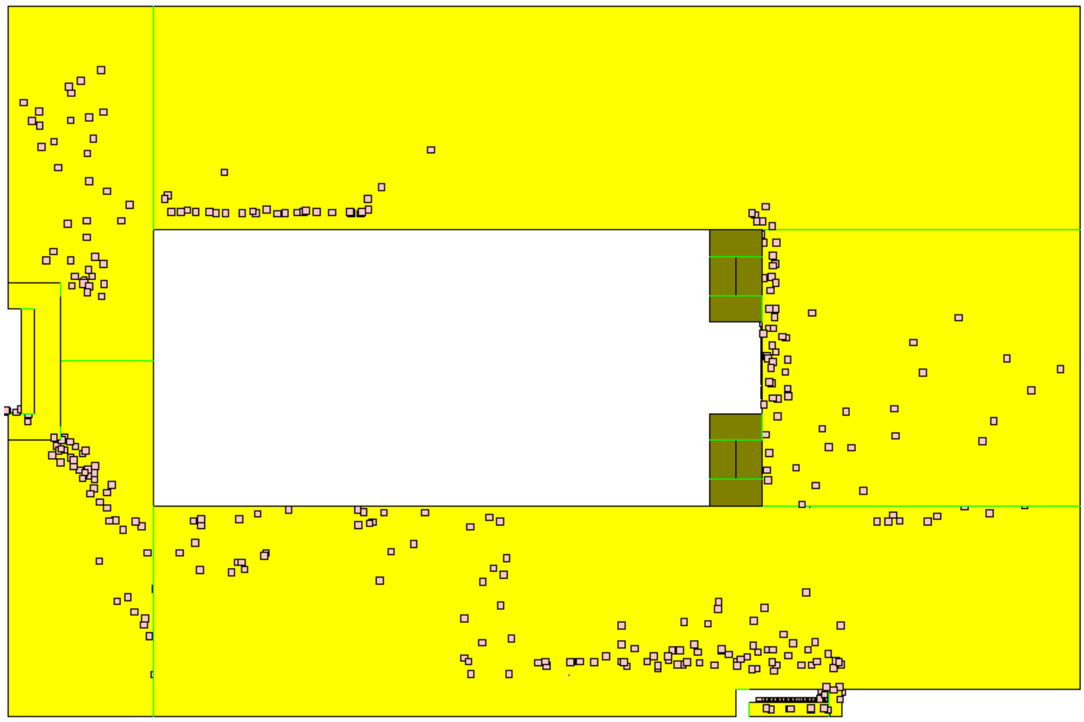


Figure 112: Exit Choice and Queuing Location for Scenario 3 - Level 7 with System

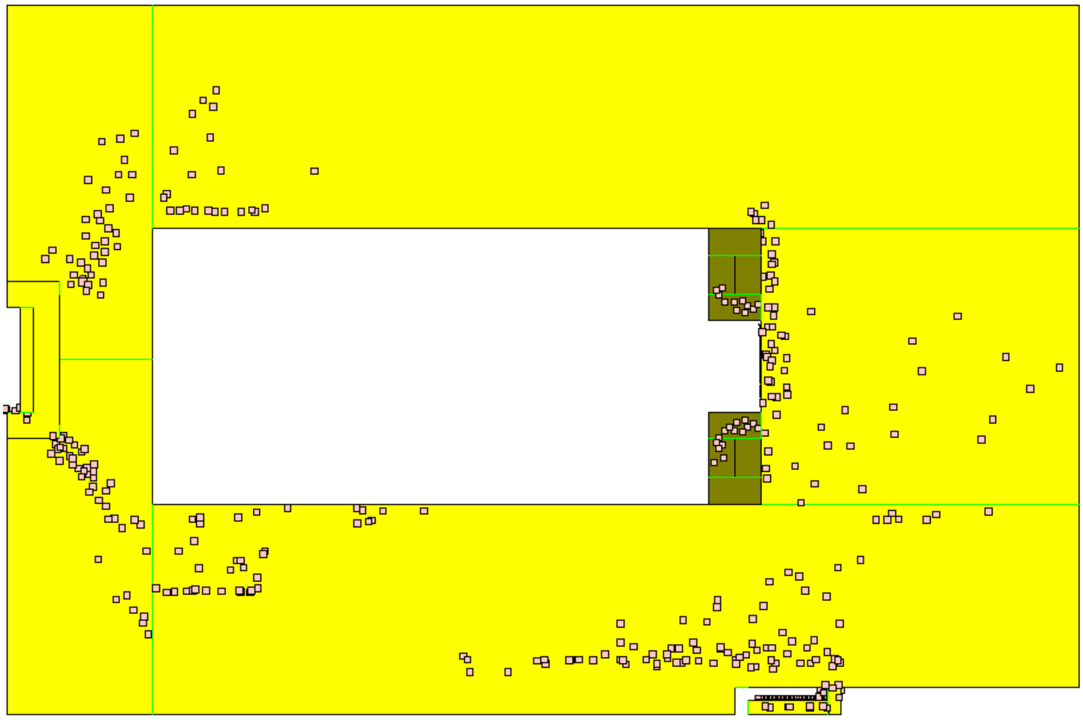


Figure 113: Exit Choice and Queuing Location for Scenario 3 - Level 7 without System

	Average Number of Occupants		Average Percentage	
	With System	Without System	With System	Without System
Stair 1	1338	1166	53.6%	46.7%
Stair 2	0	172	0.0%	6.9%
Stair 3	0	148	0.0%	5.9%
Stair 4	1158	1010	46.4%	40.5%

Table 67: Scenario 2 CRISP average number of occupants per stairwell

8.3.7 Scenario 4

The final scenario tested as part of the feasibility study was identical to scenario 3 except Stairs 1 and 4 were now affected by smoke between levels 2 and 8, leaving the egress Stairs 2 and 3 available throughout the evacuation. As with Scenario 1, the evacuation times and flow rates for the occupants within Scenario 4 are displayed in Figure 114 and Figure 115

As can be seen from Table 68 the average evacuation time and flow rate was quicker for the simulation where the system was installed within the building. This result was expected for this scenario as the two stairs that were available to be used during the evacuation where purposely designed evacuation stairwells within the building. As with the other scenarios with the system installed it is expected that no occupants will use the smoke-filled stairwell as the system will be guiding them to the safer and non-affected egress paths. Also, it is accepted that some occupants may begin to use the stairwell in the simulation without the system before they reach the smoke and have to exit the stair to change exit routes.

Scenario 4	Average Evacuation Time (sec)	Average Flow Rate (p/s)
With System	2323.8	1.21
Without System	2588.6	1.09

Table 67: Scenario 2 CRISP average evacuation time and flow rate

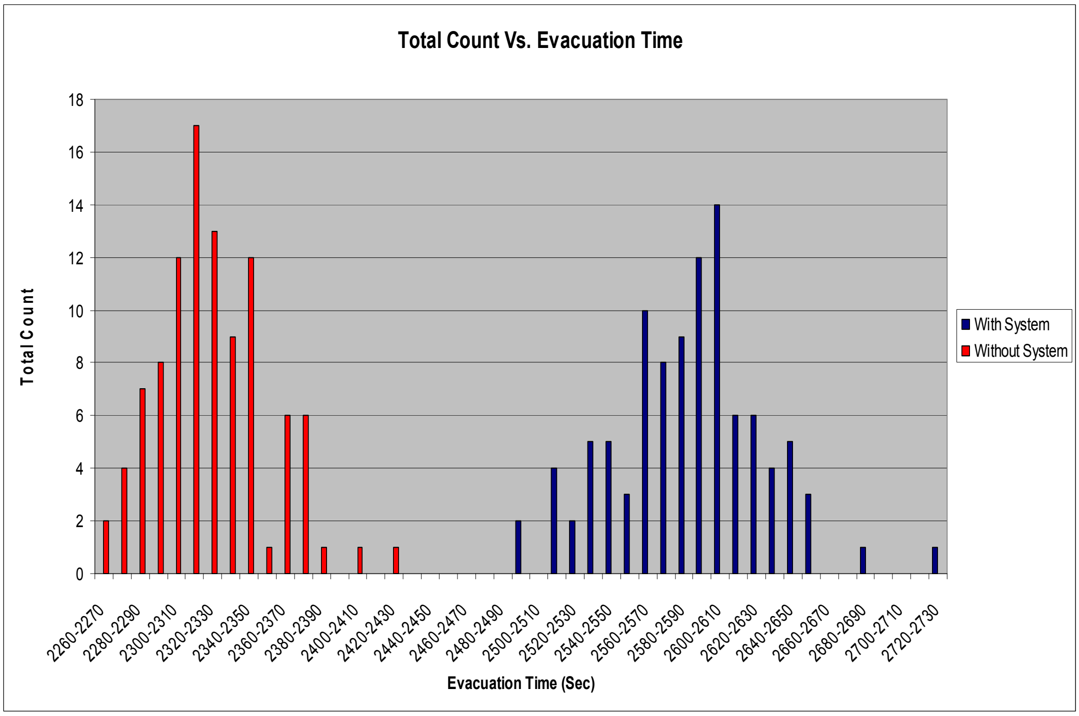


Figure 114: Total Count vs. Evacuation Time Scenario 4 with and without system

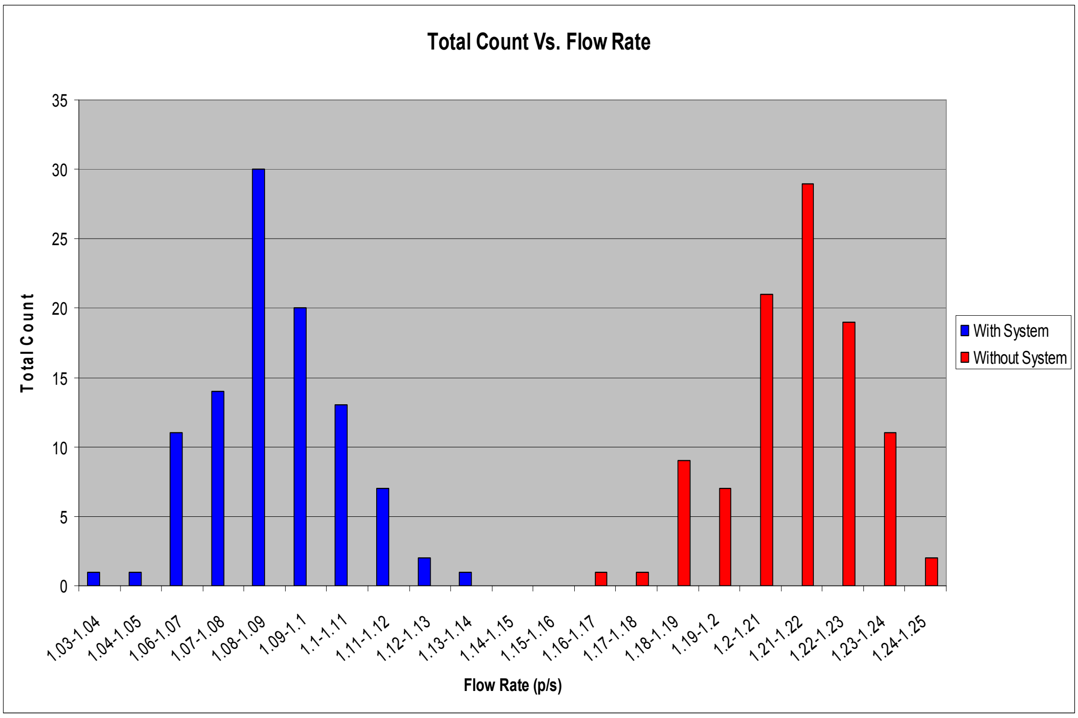


Figure 115: Total Count vs. Flow Rate Scenario 4 with and without system

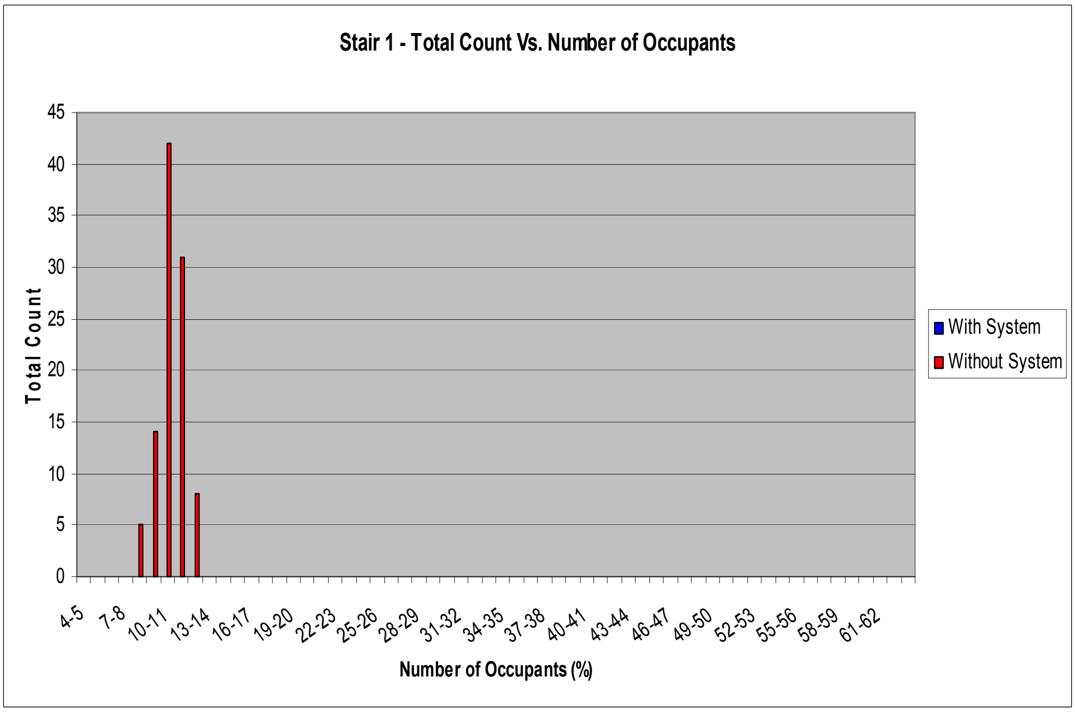


Figure 116: Stair 1 with and without system - Total Count Vs Number of Occupants

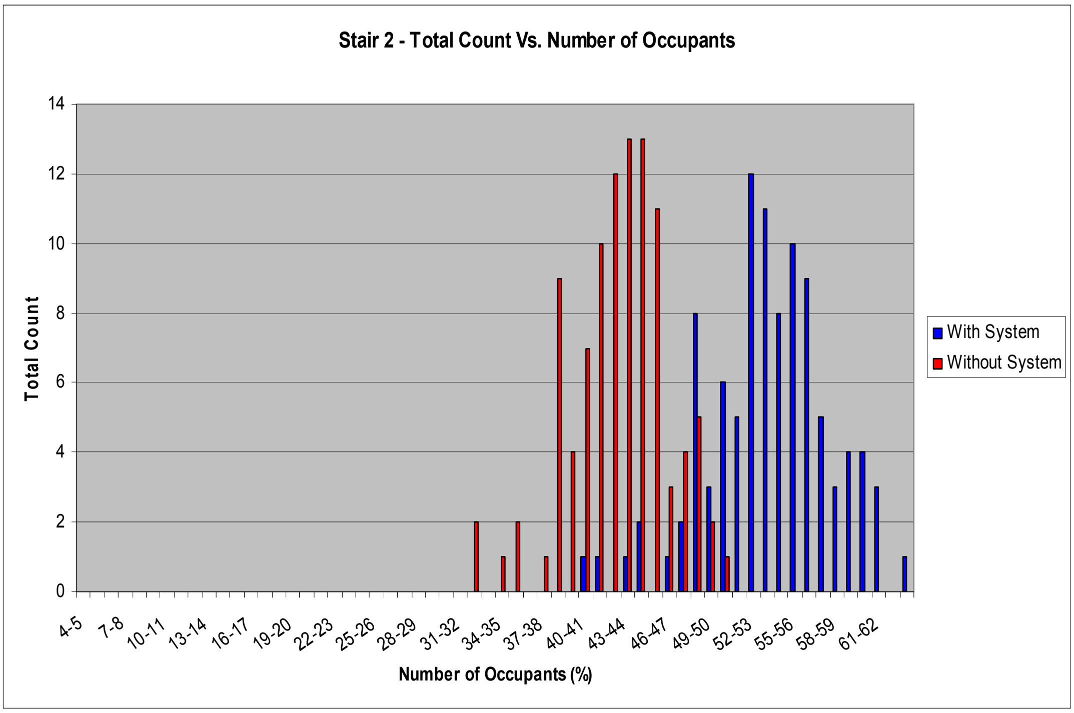


Figure 117: Stair 2 with and without system- Total Count Vs Number of Occupants

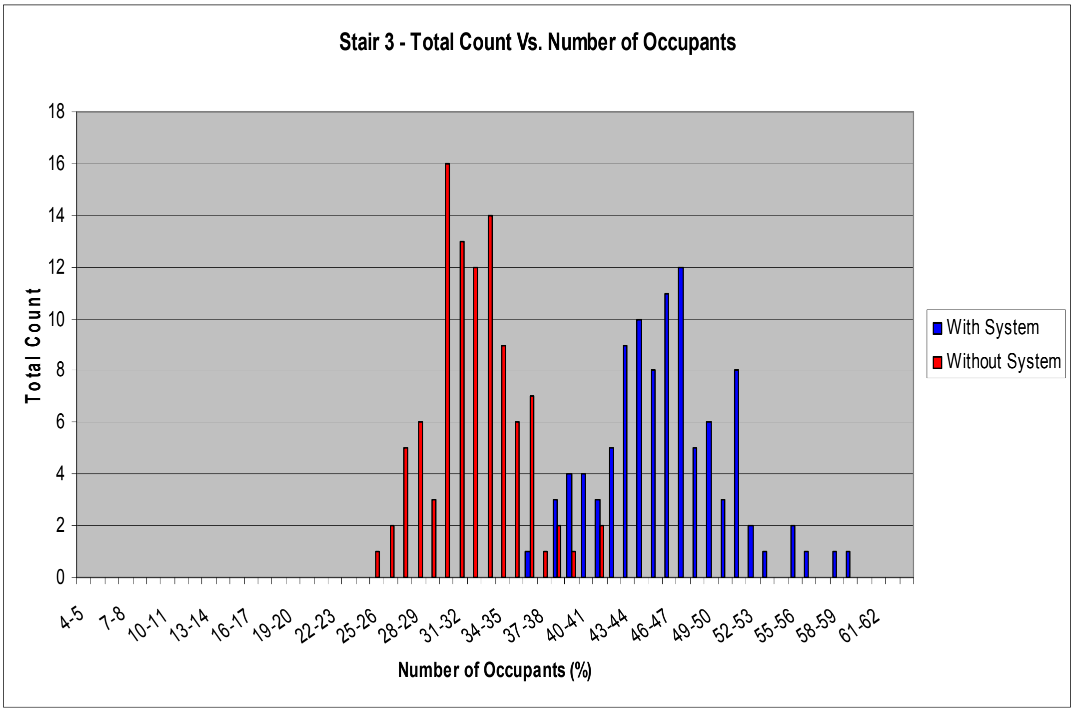


Figure 118: Stair 3 with and without system - Total Count Vs Number of Occupants

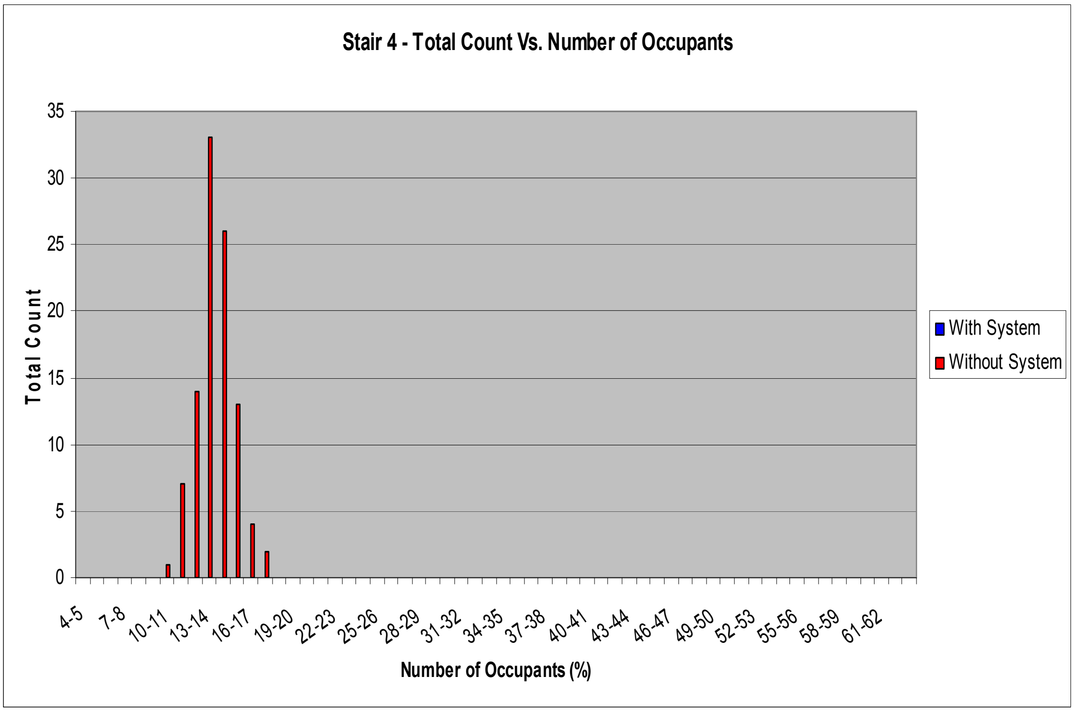


Figure 119: Stair 4 with and without system- Total Count Vs Number of Occupants

It can be seen from the results in Table 69 that the system was able to direct occupants away from using the everyday Stairs 1 and 4 with the majority of the occupants splitting almost evenly between the two available egress stairwells. Occupants who were on levels 9 to 12 chose to still use Stairs 1 and 4 until they reached the smoke within the stairwell at level 8 before deciding to use one of the other stairwells, as seen in Figure 121. As the two available stairwells were designed to take high occupant loads there was little to no effect on the horizontal and vertical movement speed due to extended periods of queuing, as seen in Figure 120.

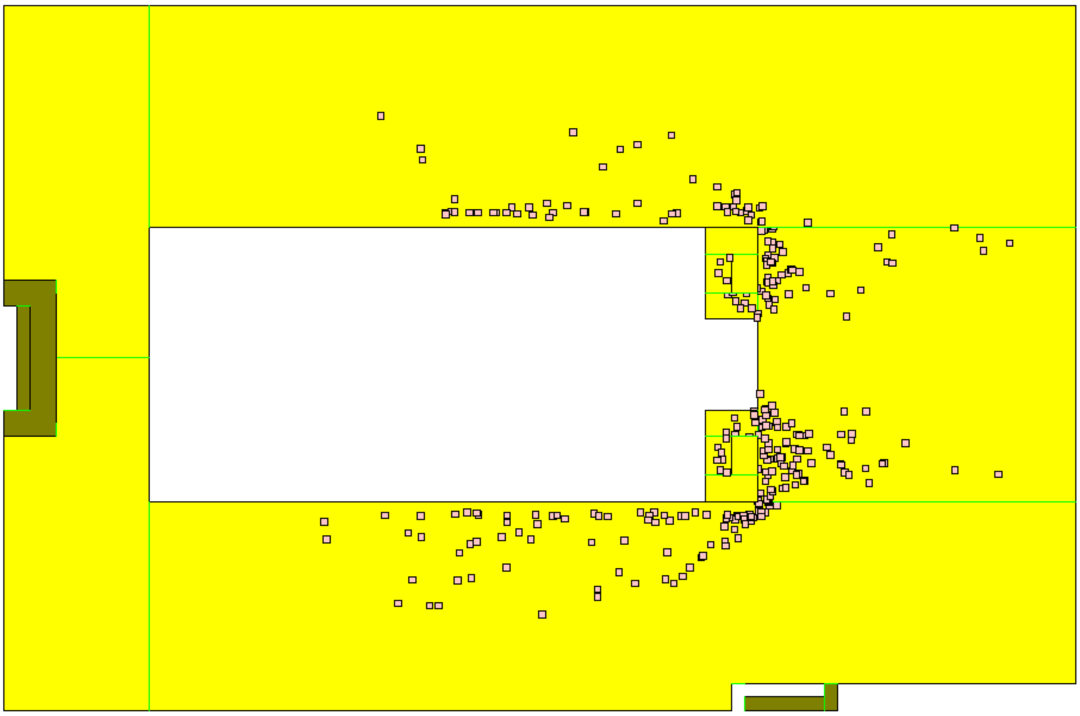


Figure 120: Exit Choice and Queuing Location for Scenario 4 - Level 7 with System (~120 Seconds)

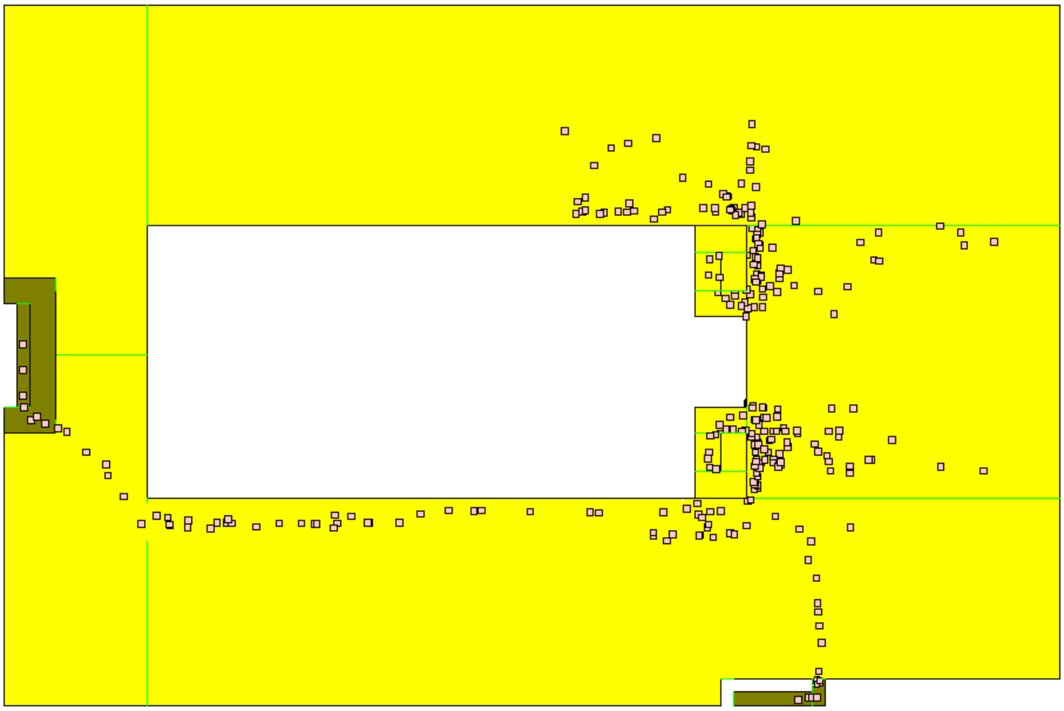


Figure 121: Exit Choice and Queuing Location for Scenario 4 - Level 7 without System (~120 Seconds)

	Average Number of Occupants		Average Percentage	
	With System	Without System	With System	Without System
Stair 1	0	268	0.0%	10.7%
Stair 2	1338	1070	53.6%	42.9%
Stair 3	1158	811	46.4%	32.5%
Stair 4	0	347	0.0%	13.9%

Table 68: Scenario 2 CRISP average number of occupants per stairwell

8.3.8 Comparing all scenarios

The final stage of the feasibility analysis is to compare the average evacuation time and flow rate for each scenario against the base case, scenario 1, in order to see if the model is producing results that are similar to that expected based on the behaviour discussed within Chapters 3, 7 and 8. The results comparing all scenarios are shown in Figure 122, Figure 123, and Table 70. The average evacuation time was considered to be the overall defining assessment factor for the feasibility study as it took into account the effects of the behavioural choices of the occupants (with and without the use of the system), the effects of the smoke and the queuing (with and without the system) and the overall walking speeds achieved by the occupants (with and without the system).

Scenario	With System?	Average Evacuation Time (sec)	Average Flow Rate (p/s)
1	N	1920.9	1.47
2	Y	1981.7	1.42
	N	2055.4	1.37
3	Y	2917.0	0.97
	N	2607.3	1.08
4	Y	2323.8	1.21
	N	2588.6	1.09

Table 69: Scenario 2 CRISP average evacuation time and flow rate

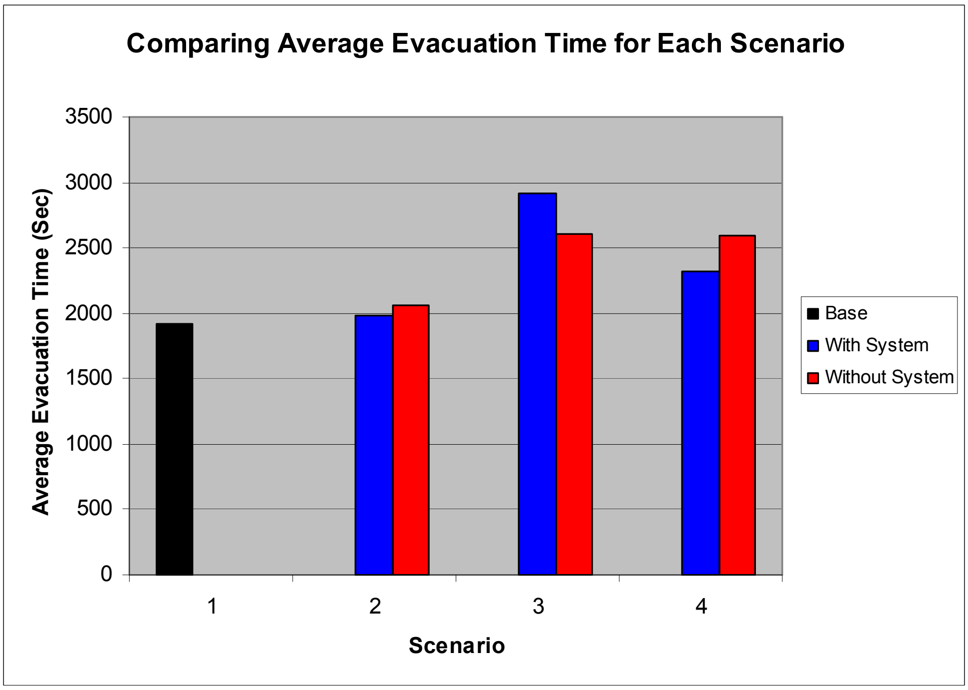


Figure 122: Comparing Average Evacuation Time for Each Scenario

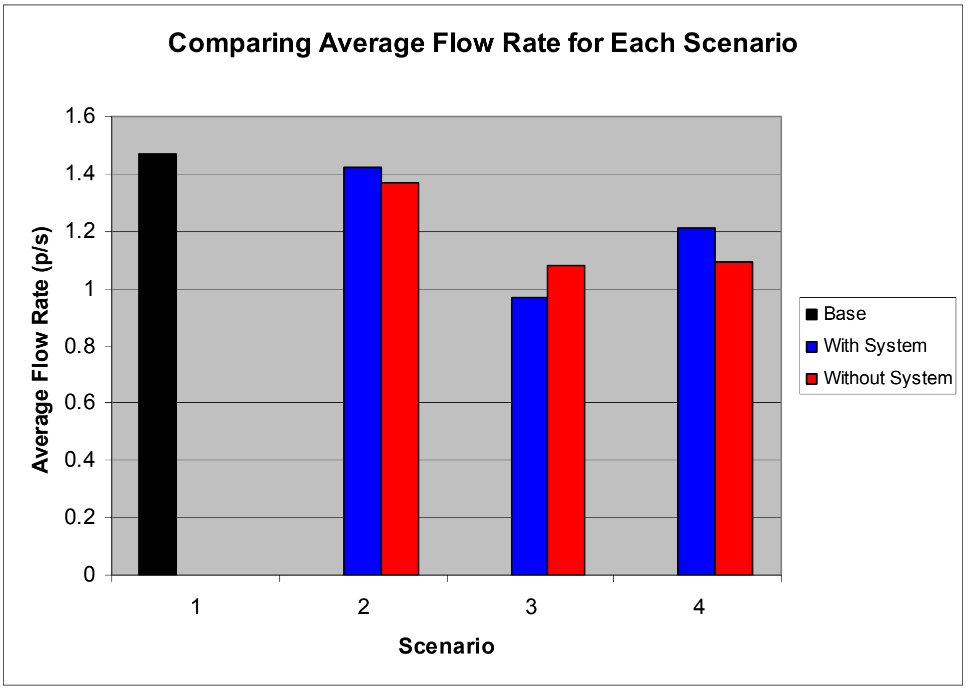


Figure 123: Comparing Average Flow Rate for Each Scenario

As expected the base case scenario had the fastest overall evacuation time out of all the models conducted, due to the fact all the egress routes were available and unaffected by smoke.

Removing one of the two egress stairs did increase the evacuation time slightly but not as significantly as removing both of the egress stairs. By relying on the everyday stairs (Stairs 1 and 2 as seen with scenario 3) the average evacuation time increased with and without the system while the flow rate decreased. As discussed within section 8.3.6 the significantly larger evacuation time during scenario 3 with the system install compared to without the system was due to the queuing caused by using the smaller stairwells, which were not designed to take such high occupant loads, and a significant increase in the occupant load of the stairs.

Even though within scenario 4 both egress stairs were available the evacuation time was still larger than that of scenario 1 and 2, which was also the case for the average flow rates, as due to the effect of the increased queuing at the doors. However, as the stairs available within scenario 4 were designed to take higher egress loads the queuing effects experienced by the occupants was reduced as the larger doors and stair widths allowed for more occupants to move through the stairs at a higher rate compared to the everyday stairs.

8.3.9 Discussion & conclusion

The purpose of the feasibility study was to examine the effects of using way-finding tools, within the modelling program CRISP, to demonstrate how the intelligent egress system could possibly be used during an evacuation based on the behaviour witnessed during the three live evacuations conducted. Combining the behaviours discussed previously in Chapter 7 and the behaviours witnessed previously within Chapter 8, the modelling program, CRISP, was modified. This feasibility study aimed to determine whether or not the proposed sensor-linked system is a viable option/tool to use during an emergency evacuation

The first stage was to determine which egress routes the occupants within the model would favour if there was no potential danger present which was determined by conducting a full building evacuation trial. This scenario, known as scenario 1, showed that the majority of the occupants favoured using one of the two purposely designed egress stairs with a small majority of occupants choosing to use the everyday stairs if they were located nearer to them. Hence, all other scenarios conducted as part of the feasibility study were compared to the base case scenario.

The second stage of the analysis was to determine if the models were able to guide the occupants away from the affected stairs successfully but still give the occupants the chance to use the stairs if they desired. Within the models with or without the system installed, occupants did initially begin to use the affected stairs with the number of occupants being significantly lower when the intelligent egress system was used. The occupants who did use the smoke-filled stairs chose their egress route based on relative distance to the exit doors and once they encountered the smoke within the stairs they often changed their exit choice and moved out of the affected area to find an alternative route.

As expected, by removing the ability to use various exits within the building the overall evacuation time increased, hence, the overall flow rate of the occupants decreased. However, the amount that these two factors was influenced varied based on the stairs that became affected. In the scenario where only one of the two egress stairs were affected the overall, evacuation time increased by 3% and 7% with and without the system, respectively. However, for the scenario where everyday stairs were affected, the overall evacuation time increased by 21% and

35% with and without the system, respectively. The most significant evacuation time increase occurred during the scenario where both egress stairs were affected by smoke with an overall increase of 52% and 36% with and without the system respectively. The increase in the overall evacuation time was due to reducing the number of available egress routes which led to a significant increase in queuing experienced by the occupants.

Queuing was experienced throughout all of the scenarios, regardless of the availability of each egress routes. However, the effects of queuing were significantly increased when the egress stairs were made unavailable during the evacuation. As seen above within Scenario 3 the overall increase in evacuation time was significantly higher for the model without the egress stairs. However, when the building was provided with the system the evacuation time increased significantly, which initially was determined as a failure of the coding of the model. However, on further analysis, it could be seen that the occupants, within the building without the system, upon levels 9 – 12 still used the egress stairs, as the smoke was at a high enough density to prevent egress movement, and once they had reached a situation where the smoke density was to significant for egress they choose an alternative route. By the time the occupants began to find an alternative route the queue upon levels 3 – 8 was significantly reduced, hence, the occupants on 9 – 12 were able to use the everyday stairs with a reduced queuing time. In the building with the system all occupants headed towards the everyday stairs, which were not designed for a high occupant load, hence queuing was far more intense. Even though it took longer for the occupants to evacuate the building the system was still able to perform its primary objective which was to guide occupants away from the smoke affected routes.

The successes of the model came down to a series of basic human behaviours described within Chapter 3 and 6 and witnessed during all the live evacuations, which included a behaviour known as "following the leader". This behaviour was prominent during the evacuation experiments, which shows that if a leading occupant chose a specific route, either on their own or after being influenced, the occupants behind them would follow their exit choice. CRISP has the ability to associate different behavioural sets to occupants at random based on user input, hence, within the model some of the occupants were demonstrating "leadership qualities". Once these occupants head towards the exit the occupants around them follow their exit choices. This is the reason why, during some evacuations, occupants used the stairs that were affected by smoke before finding an alternative route as the occupants decided to follow the leading occupant in the initial stages of the simulation until their behavioural set told them to move away from the smoke, based on the optical density.

The behaviour of the occupants within the model showed that when the way-finding lights were in use the majority tended to choose to stay away from the affected exits and find alternative routes. There were a few occupants who initially chose to use the affected stairs as there was no smoke present within them upon their levels. After descending the stairs a few levels the occupant came across the smoke within the stairs and chose to exit via an alternative route. This behaviour was witnessed during the live evacuation experiments to some extent with the occupants heading towards the everyday exits before turning around due to either the way-finding system or information from other occupants.

The feasibility study conducted showed the effects of using an intelligent egress system during an evacuation, based on the information gathered from the live experiments and the background research into human behaviour. Providing CRISP with way-finding tools, both audio and visual in accordance with the live experiments, allowed for the program to guide occupants away from potential dangerous situations and towards an area of safety. The extra information given to occupants allowed them to assess the situation they were in and helped guide them away from the unavailable exits, which did significantly increase the overall evacuation time in some cases compared to that of the base scenario where all exits were available.

Even though the evacuation time increased and the flow rates decreased the intelligent system was successful at guiding occupants away from a dangerous situation to one of safety. As all occupants were unaffected by the smoke from the fire it would be considered a success based on the basic principal of the intelligent system, to guide occupants to an available and safe exit route to prevent loss of life. Hence, the study demonstrated the importance of providing occupants with up-to-date information whilst showing the effects of the removal of purposely designed egress route on the flow rate, evacuation time and queuing experienced.

The study showed how the system would work in an ideal situation, where all occupants understood and adhered to the information provided by the way-finding tools. Even though the study can demonstrate a small proportion of the complexities of the true behaviours of the occupants that would occur in real life, it was able to validate the assumptions on the occupants interactions made within the experiments conducted as part of this thesis. To truly understand how occupants would interact with the system, further work would be required which would consolidate into conducting a full-scale intelligent system trial within an existing office building.

9 Discussion & Concluding Summary

As stated in the very first paragraph of this thesis, the effectiveness of an emergency response during an incident is often affected by the lack of unambiguous, relevant information provided by the current conditions. The aim of the work conducted during this thesis was to develop a new intelligence driven evacuation system that was able to address known behavioural limitations within the egress solution design process. The aim of this development was to ensure occupants were provided with timely and accurate information on a development of a fire and the availability of egress routes. This development was based on a new method of providing occupants with up-to-date information that incorporated live information on the evolution of a fire in order to predict its development and impact on the egress routes available.

The system addressed the assumption often made during the design of an evacuation plan that evacuees will respond as expected, irrespective of the information received. However, this assumption was often incorrect and has been consistently demonstrated throughout evacuation literature and during the evacuation experiments conducted within this thesis. Evacuation plans also assume that the information provided to the occupants will allow them to fully comprehend the egress routes within the building without causing a delay, or even worse, walking in the wrong direction. However, as discussed within Chapter 1 and 3, the behavioural patterns assumed during the creation of an evacuation plan are not necessarily followed in a real incident leading to a delay in occupants reaching a place of safety during an emergency scenario. An example of a behavioural pattern that can affect an evacuation plan is the occupants desire to exit the building through the entrance they came in, as it is familiar and assumed to be safe. This behaviour may lead to some of the occupants missing or ignoring closer and/or safe alternative exit routes, especially where the route to their familiar exit is affected by effluent. The I.D.E.S. was developed to address these performance issues.

In order to demonstrate that the information provided by the I.D.E.S. will be able to improve the processes/efficiency of an evacuation a series of experiments were conducted to demonstrate that the use of positive and negative information from way-finding tools could improve the chances of the occupant egressing along the desired routes (i.e. those required as part of the emergency procedure). It was hoped that each of the experiments conducted could be used to configure the I.D.E.S., provide insight into the behaviours being addressed and allow the predictive performance of the tool to be examined.

The experimental data indicate factors and outcomes not addressed by the existing model. The data then both suggested and enabled the development of new code, by the author, which enhanced the predictive capabilities of the tool; i.e. to better predict how way-finding tools might influence evacuee decisions. Care was taken to ensure that the experiment conditions were representative of a real emergency scenario; e.g. using fake smoke and acetic acid, or conducting unannounced evacuation drills.

The first experiment series demonstrated the occupants' ability to adapt to an unknown situation and evacuate from the train more efficiently. The second experiment series conducted provided detailed data on the effectiveness of a wide range of way-finding installations, the impact of exit design and highlighted the importance of providing information to occupants. It demonstrated that providing occupants with active information could influence their movement speed and movement patterns when within an unknown situation and environment. It also further highlighted the evacuee's ability to cope/learn (from the environment and the signage); for instance, a significant majority of participants quickly used the tunnel walls to navigate through the smoke-filled environment.

The main purpose of the experiment was to analyse the effect of different emergency exit designs and way-finding installations according to their ability to attract the participants. Of the installations tested, the door equipped with a loudspeaker, which broadcasted an alarm signal and a voice message, was found to be the most effective at attracting the participants to the exit. The least effective was the combination of a continuous green and white source with a strong halogen lamp. This installation was misinterpreted by many of the participants as a train even though the lights were visible through the dense smoke: it led to the participant avoiding using the exit due to the associated uncertainty.

The data gathered from the experiment allowed the author to determine which of the way-finding tools would be useful assets as part of the I.D.E.S., which tools were the most successful in guiding the occupants to the exit, and which therefore tools to focus on during the development of the source code for the predication models. The experiments tested how the different installations worked within a tunnel environment.

The third set of trials examined the effectiveness of different systems in a building.

The final experiment series conducted showed that it was possible to influence an occupant's exit choice, using way-finding tools, when the preferred route from a building is unusable. It demonstrated that providing the occupant with extra information allowed them to better assess the situation and guided them towards safety.

These experiments provided data on the impact of using way-finding tools to provide negative and positive information, to participants and highlighted how their behaviours could affect the success of the evacuation process. The dominant behaviour present in the first experiment was the use of the familiar main exits from the building. The dominant behaviour observed in the second experimental run was participants taking time to investigate the closure of the main exit while discussing with other occupants about the possible egress routes still available. Furthermore, these experiments demonstrated how the removal of a building's main egress route could influence the movement speed, movement paths and behaviours of the occupants. These results were useful for the development of the system as it lead to further improvement of the source code and hence the predictive capabilities of the program.

The main purpose of the experiments was to test whether it is possible or not to influence an occupant's exit choice, using way-finding tools, when the preferred route was unusable – effectively when the primary choice for evacuees was not available. Various visual and audible systems were examined, with green LEDs and a speaker providing information on the location of an available exit being deemed most effective. Although limited to the test environment (a relatively simple space), the results are indicative.

The final part of the thesis described a feasibility study, where the impact of way-finding tools was modelled using the CRISP tool. This enabled the effectiveness of the wayfinding tools to be tested in a new environment and the effectiveness of the newly implemented model to be assessed. The model for the study combined the behavioural information gathered from the experiments conducted, the information gathered during the background research conducted and the code developed. The study showed how the system would work in an ideal situation, where all occupants understood and adhered to the information provided by the way-finding tools. Even though the study can demonstrate a small proportion of the complexities of the true behaviours of the occupants that would occur in real life, it was able to validate the assumptions on the occupants interactions made within the experiments conducted as part of this thesis. To truly understand how occupants would interact with the system, further work would be required which would consolidate into conducting a full-scale intelligent system trial within an existing office building.

Based on the results of the feasibility study the information provided to the simulated occupants by the wayfinding system allowed them to assess the situation they were in and helped guide them away from the unavailable exits – as was seen during the experiments. This increased the overall evacuation time in some cases, compared to that of the base scenario where all exits were available. However, even though the evacuation time increased the simulated wayfinding guidance system directed occupants away from a dangerous situation to one of safety. The model was then able to represent the effectiveness of the guidance system and might then inform the I.D.E.S. system if implemented with an operational system.

The goal of this thesis was to begin the development of an intelligent system that incorporated the use of way-finding tool, sensors and prediction models that when combined were able to improve the efficiency of the evacuation process based on the available egress routes and the development of the environmental conditions. Even though there is still significant work to be conducted before the system is completed, this thesis was able to develop the fundamental idea and the processes that would be required to be conducted by the system, as well as begin the development of the behavioural/egress prediction modelling tool to be incorporated within the system.

The primary contribution of this research was the development of a new predictive modelling tool, based on an already verified and validated code, which can be used to predict the influence of different types of way-finding tools on an occupant's egress choice based on the collection and incorporation of experimental data. The model developed as part of the thesis was created to be used within the I.D.E.S. system as the main prediction tool for both the egress movement/behavioural patterns of the occupants. Previously, work completed by Dr Sung-Han Koo K-CRISP demonstrated the chosen programme's ability to predict the development of a fire with the use of sensor information, while the egress model within this thesis showed the potential influence of the system on the occupants by using varying information provided by the way-finding tools. The purpose of the predict egress model within the functioning version of the I.D.E.S. system is to influence and predict the movement patterns of the occupants and to guide them to towards a safer exit route with the aim of reducing their exposure to hazardous conditions (i.e. smoke). The ideal scenario of how the system would complete this task was demonstrated within the feasibility study conducted within this thesis.

The modelling program within this thesis is owned by the BRE and is not for public use at this stage of development. The source code and the overall program will be further developed by the next BRE PhD student employed as part of the research team at the BRE centre of Fire Engineering at the University of Edinburgh, Scotland. The following chapter is a description of the process that the author of this thesis would have followed as part of the future development of the system.

10 Future Work

The work described within this thesis was limited mainly by time and financial constraints. This influenced the level and scale of the experiments conducted as part of the research. Even though the experimental data gathered provided a significant amount of the information required to further develop the CRISP modelling program (to be used as part of an intelligent egress system), still more work is required to improve the system and the program. The following describes the work the researcher would conduct given sufficient time and resources.

The predictive capabilities of the modelling programme developed as part of the experiments discussed within Chapters 8 would be enhanced. This would involve conducting further live evacuations that had the occupants relying on way-finding tools in order to evacuate the facility.

Further large scale experiments should be conducted to see how the system could be used to not only influence the horizontal movement of the occupants but their vertical movement as well, given audio and visual notification. These might include experiments examining:

- the pre-evacuation times and preferred egress routes chosen when evacuating the building during an evacuation involving the alarm in situ.
- Install audio/visual tools and conduct an unannounced trial to examine how the occupants react to the removal of the most commonly used egress route and the impact of the way-finding tools installed on the routes adopted; i.e. identify the willingness of untrained occupants to follow information provided by the system.
- Train participants in the wayfinding tools to be employed, and then repeat the previous trial to examine the impact of training on performance.

The next phase of testing for the system would require the installation of the full system, which would include installing the appropriate sensors and way-finding tools within each room of a small office space or similar building. The system would be connected to the modelling program and specific sensors would be activated, using artificial smoke, in order to test if the system would have the ability to change the way-finding tools setting to provide the information predicted/required.

All previous information gathered would be consolidated into a full-scale evacuation of a high-rise building that would have the full intelligent, sensor-linked egress system installed throughout. As part of the experiment, artificial smoke would be introduced into one of the egress routes of the building in order to activate the corresponding sensors. This would result in the system altering the information provided by the installed way-finding tools with the aim of guiding the occupants towards a specific egress route. This experiment would involve considerable resources (given technical, ethical and methodological factors), while requiring input from a wide range of parties, including the fire service, the building's owners, insurance company and the research team etc. This experiment would not only demonstrate how the system works within a building, but would produce information that could be used as part of a study looking into pre-movement behaviour, evacuation behaviours, walking speeds and the effects of queuing.

It should be noted that the following will not be discussed further within this section as at the time of re-writing this thesis another student from Edinburgh University was intending to undertake this research:

- The process of developing the connection between the physical components of the system

- The processes required to link the information from the sensors to the prediction modelling program

- The development of the interface for the I.D.E.S.

It should also be noted that the prediction modelling program will be constantly updated and upgraded as new information is gathered from each of the experiments stated below. Each of the following experiments are considered to be necessary in order to gather specific information for improving the prediction capability of CRISP. For each experimental series described, *a priori* and a *posterior* models are to be conducted to further test the prediction capabilities of the models.

11 Reference

[1]. J.D. Sime, “Affiliative Behaviour during Escape to Building Exits”. Journal of environmental psychology 3, pp. 21 – 41. Jonathan Sime Associates, Godalming, Surrey, UK, 1983.

[2]. G. Jensen, “Wayfinding in Heavy Smoke: Decisive Factors and Safety Products. Findings Related to Full Scale Texts”. Fire Safety vol. 98, Fire Protection in Nuclear Installations IGP AS, Mumbai, 1998.

[3]. J.D. Sime, “Crowd psychology and engineering. Safety Science”, vol. 21, pp. 1-14. Jonathan Sime Associates, Godalming, Surrey, UK., 1995.

[4]. "The Fire at Woolworth's, Piccadilly, Manchester, May 8, 1979: Report of the Planning/Legislation Subcommittee, Joint Fire Prevention Committee of the Central Fire Brigades Advisory Councils for England and Wales and for Scotland," Home Office, Fire Department, London, 1980.

[5]. “Task Force for Technical Investigation of the 24 March 1999 Fire in The Mont Blanc Vehicular Tunnel – Report of 30 June 1999 (English Translation)”, Minister of the Interior, and Ministry of Equipment, Transportation and Housing, 1999.

[6]. British Standard Institution, 389 Chiswick High Road, London, BS 5839-1, “Fire detection and fire alarm systems for buildings. Code of practice for system design, installation, commissioning and maintenance”, 2008

[7]. E. Kuligowski, “The process of human Behaviour in Fires’, National Institute of Standards and Technology, NIST Technical Note 1632, May 2009.

[8]. C.D. Wickens and J.G. Hollands, “Engineering psychology and human performance”, Prentice Hall, pp. 50 - 65, 2000.

[9]. British Standard Institution, 389 Chiswick High Road, London, BS 5839-1, “Fire detection and fire alarm systems for buildings. Code of practice for system design, installation, commissioning and maintenance”, 2008

[10]. J. Fraser-Mitchell, S.H. Koo, and S. Welch, “Sensor-linked simulation for emergency response” in Human Behaviour in Fire Symposium 2009, pp. 561 – 566. BRE Global, UK, the University of Edinburgh, UK, 2009.

[11]. L. Benthorn, and H. Frantzich “Fire alarm in a public building: How do people evaluate information and choose evacuation exit?” Department of Fire Safety Engineering, the University of Lund, Sweden, 1996.

[12]. S.H. Koo, “Forecasting fire development with sensor-linked simulation”, PhD, University of Edinburgh, 2010.

[13]. I. Miller, “Human Behaviour Contributing to Unintentional Residential Fire Death 1997 – 2003”, Heimdall Consulting Ltd, Feb 2005.

[14]. M.K. Kowalski- Trakofler, C. Vaugh, and T. Scharf. “Judgement and decision making under stress: an overview for emergency managers” Vol. 1, Number 3.2003, Interscience Publishers, pp. 278-289, February 2004.

[15]. G. Proulx, “A Stress model for people facing a fire’. Journal of Environmental Psychology, Vol. 13, Issue 2, pp. 137 – 147, June 1993.

[16]. G. Proulx, “Evacuation time and movement in apartment building”, Fire Safety Journal, Vol. 24, Issue 3, pp. 229 – 246, 1995.

[17]. J.M. Darley, and B. Latane. “Bystander intervention in emergencies: Diffusion of Responsibility.”, Journal of Personality and Social Psychology, Vol 8 (4, Pt.1), pp. 377-383, April 1986.

[18]. J.D. Sime, "Escape Behaviour in Fires and Evacuations," in Design Against Fire: An Introduction to Fire Safety Engineering Design, Chapman & Hall, London, 1994.

[19]. S. Horiuchi, Y. Murosaki, and A Hokugo. “A Case Study of Fire and Evacuation in a Multi-Purpose Office Building, Osaka, Japan.” Proceedings of the First International Symposium of IAFSS. P. 523-532, 1985.

[20]. C.D. Wickens and J.G. Hollands, “Engineering psychology and human performance”, Prentice Hall, pp. 50 - 65, 2000.

[21]. Tower Hamlet Council. [Online]. Available: www.towerhamlets.gov.uk

[22]. L. Benthorn, and H. Frantzich "Fire alarm in a public building: How do people evaluate information and choose evacuation exit?" Department of Fire Safety Engineering, the University of Lund, Sweden, 1996.

[23]. M.A. Stall, "Stress, Cognition, and Human Performance: A Literature Review and Conceptual Framework". Ames Research Center, Moffett Field, California, NASA/TM, 212824, August 2004.

[24]. X. Pan, C.S. Han, K. Dauber, and H.K. Law, " Human and social behaviour in computational modelling and analysis of egress", Automation in Construction, vol. 15, Issue 4, pp. 448-461, July 2006.

[25]. J.D. Sime, "Affiliative Behaviour during Escape to Building Exits". Journal of environmental psychology 3, pp. 21 – 41. Jonathan Sime Associates, Godalming, Surrey, UK, 1983.

[26]. G. Jensen, "Wayfinding in Heavy Smoke: Decisive Factors and Safety Products. Findings Related to Full Scale Tests". Fire Safety vol. 98, Fire Protection in Nuclear Installations IGP AS, Mumbai, 1998.

[27]. J.D. Sime, "Crowd psychology and engineering. Safety Science", vol. 21, pp. 1-14. Jonathan Sime Associates, Godalming, Surrey, UK, 1995.

[28]. J. Barylick, "Killer Show – The station Nightclub Fire, America's Deadliest Rock Concert", University Press of New England, 2012.

[29]. "Technical Investigation Report concerning the Fire on Eurotunnel freight Shuttle 7412 on 11 September 2008 (English translation)", Department for Transport and Rail Accident Investigation Branch, November 2010.

[30]. G. Proulx, I. Reid, N. Cavan, "Human Behaviour Study Cook County Administration Building Fire Octover 17, 2003 – Chicago, IL.", National Research Council Canada, April 2004.

[31]. D. Nilsson. "Exit Choice in Fire Emergencies – Influencing choice of exit with flashing lights", Department of fire safety engineering and systems safety, Lund University, Sweden, Doctoral Thesis, Lund 2009.

[32]. T.R. French, "Evolutionary Optimisation of Networked Flow Paths for Emergency Movement in the Building Environment", PhD, University of Edinburgh, 2011.

[33]. Department of Building and Housing New Zealand "Compliance Document for New Zealand Building Code Clauses C1, C2, C3, C4 Fire Safety", 2010.

[34]. British Standard Institution, 389 Chiswick High Road, London, BS 9999:2008, "Code of practice for fire safety in the design, management and use of buildings", 2008.

[35]. Chartered Institution of Building Services Engineers London, "Fire engineering CIBSE Guide E", Second Edition, September 2003.

[36]. British Standard Institution, 389 Chiswick High Road, London, PD 7974-6:2004, "The application of fire safety engineering principles to fire safety design of buildings – Part 6: Human factors: Life safety strategies – Occupant evacuation, behaviour and conditions (sub-system 6)", 2004.

[37]. British Standard Institution, 389 Chiswick High Road, London, BS EN 54-14, "Fire detection and fire alarm systems Part 14. Guidelines for planning, design, installation, commissioning, use and maintenance", 2011.

[38]. British Standard Institution, 389 Chiswick High Road, London, BS EN 54-3:2001, "Fire detection and fire alarm systems Part 3: Fire alarm devices – Sounders", 2001.

[39]. British Standard Institution, 389 Chiswick High Road, London, BS EN 54-8:2008, "Fire detection and fire alarm systems Part 8: Code of practice for the design installation, commissioning and maintenance of voice alarm systems", 2008.

[40]. British Standard Institution, 389 Chiswick High Road, London, BS EN 54-14, "Fire detection and fire alarm systems Part 14: Guidelines for planning, design, installation, commissioning, use and maintenance", 2013 (in development).

[41]. British Standard Institution, 389 Chiswick High Road, London, BS 5839-8:2008, "Fire Alarm Voice Evacuation Systems", 2008.

[42]. British Standard Institution, 389 Chiswick High Road, London, BS EN 54-1:2011, "Fire detection and fire alarm systems Part 1 Introduction", 2011.

[43]. British Standard Institution, 389 Chiswick High Road, London, BS 8456:2005, "Code of practice for design and installation of directional sounder evacuation systems", 2005.

[44]. British Standard Institution, 389 Chiswick High Road, London, PAS 41:2003, "Publicly available specification, Directional Sounders – Requirements and tests", 2003.

[45]. British Standard Institution, 389 Chiswick High Road, London, BS EN 1838:1999 / BS 5266-7:1999, "Lighting Applications – Emergency Lighting", 1999.

[46]. British Standard Institution, 389 Chiswick High Road, London, BS 5266-1:2011, "Emergency lighting – Part 1: Code of practice for the emergency escape lighting of premises", 2011.

[47]. British Standard Institution, 389 Chiswick High Road, London, BS EN 54-23:2010, "Fire detection and fire alarm systems Part 23: Fire alarm devices – Visual alarm devices", 2010.

[48]. British Standard Institution, 389 Chiswick High Road, London, BS EN 5499-4:2000, "Safety Signs, including fire safety signs", 2000.

[49]. British Standard Institution, 389 Chiswick High Road, London, DRAFT EN 16276, "Evacuation Lighting in Road Tunnels", May 2011.

[50]. National research council Canada and Public works and Government Service Canada, "Guide for the installation of Photoluminescent Exit Stairway Marking in Buildings", 2008. [Online]. Available: http://archive.nrc-cnrc.gc.ca/obj/irc/doc/pubs/nrcc50818/nrcc50818.pdf

[51]. S. Potter, G. Beckett, G. Pringle, S. Welch, S.H. Koo, G Wickler, A. Usmani, J Torero, and A. Tate "FireGrid: An e-infrastructure for next-generation emergency response support" in Journal of Parallel and Distributed Computing, vol. 70, Issue 11, pp. 1128 – 1141, November 2012.

[52]. M. Slater, and P. Topol, "Intelligent Fire Safety System United States Patent". Patent Number: 4531114, Date of Patent: Jul 23 1985.

[53]. B.B. Pigott, "Fire Detection and Human Behaviour, International Association for Fire Safety Science, Fire Safety Science" in proceedings of the second international symposium, pp 573 – 581, 2004.

[54]. E. Miller-Hookes, and T. Krauthammer, in "An intelligent evacuation, rescue and recovery concept" in Fire Technology 2007 vol. 1, 2006.

[55]. G. Rein, C.A. Empis and R. Carvel. "The Dalmarnock Fire Tests: Experiments and Modelling", FIRESEAT proceedings, School of Engineering and Electronics, University of Edinburgh, November 2007.

[56]. C. Giachritsis, "Getaway Project", Project information 2011. [Online]. Available: http://www.getaway-project.eu

[57]. S.-H. Koo, J. Fraser-Mitchell, and S. Welch, "Sensor-steered fire simulation" in Fire Safety Journal vol. 45 (3), pp. 193-205, 2010.

[58]. C.D. Wickens and J.G. Hollands, "Engineering psychology and human performance", Prentice Hall, pp. 123 - 136, 2000.

[59]. K Fridolf, E. Ronchi, D. Nilsson., and H. Frantzich, "Movement speeds and exit choice in smoke-filled rail tunnels". [Unpublished].

[60]. D. Withington, and M. Lunch "Directional Sound Evacuation – an improved system for way guidance". Lloyds list fire science & fire investigation workshop, 13 March 2003.

[61]. D. Madrzykowski, N. Bryner, and S.I. Kerber, "The NIST Station Nightclub Fire Investigation: Physical Simulation of the Fire" at Fire Protection Engineering workshop, July 1st, 2006.

[62]. D. T. Sharpe, "The Psychology of Colour and Design", Nelson-Hall Company, Chicago, 1974.

[63]. H Benichow, and G. Proulx, "Evaluation and comparison of different installations of photoluminescent marking in stairwells of a high-rise building" at Interflam 2007, 11th international conference on Fire Science and Engineering, London. UK., pp. 1-12, Sept 3 -5 , 2007.

[64]. M.J. Kinsey, E.R. Galea, and P.J. Lawrence, "Stairs or lofts? – A study of human factors associated with lift/elevator usage during evacuation using an online survey", Fifth International Conference on pedestrian and evacuation dynamics, March 8-10, 2010.

[65]. V.M. Predtechenskii, and A.I. Milinskii, "Planning for foot traffic flow in buildings", Amerind Publishing Co. Pvt. Ltd, New Delhi 1978, (translated from original publication in Russian, 1969).

[66]. E.D. Kuligowski, and R.D. Peacock, "A review of building evacuation models", Technical Note 1471, Fire Research Division, Building and fire research laboratory, July 2005.

[67]. L. Chalmet, R. Francis, and P. Saunders. "Network models for building evacuation." Human Behaviour in Fire Symposium, Management Science, vol. 28, pp.86-105, 2009.

[68]. N Pelechano, and A. Malkawi, "Evacuation simulation models: Challenges in modelling high rise building evacuation with cellular automata approaches", Automation in Construction, vol. 17, Issue 4, pp. 337-385, May 2008.

[69]. M.A. Janssen, and E. Ostrom, "Empirically Based, Agent-based models", Ecology and Society, vol. 11, Article 37, 2006.

[70]. S. Gwynne, and E.R. Galea, "A Review of Methodologies and Critical Appraisal of Computer Models Used in the Simulation of Evacuation from the Built Environment," Research Report, Society of Fire Protection Engineers, (undated).

[71]. B. Meacham, J Lord, A Moore, G Proulx, R Fahy and K Notarianni, "Investigation of uncertainty in egress models and data", Proceedings of the 3rd International Symposium on Human Behaviour in Fire, Belfast, United Kingdom, pp. 419-428, September 2004.

[72]. G. Proulx, "Section 3, Chapter 12 – Behavioural Response to Fire and Smoke," SFPE Handbook of Fire Protection Engineering, Third Edition, Society of Fire Protection Engineers, Bethesda, MD, 2002.

[73]. D.S. Mileti, and J.H. Sorensen, "Communication of Emergency Public Warnings, A Social Science Perspective and State-of-the-Art Assessment," ORNL-6609, pp. 161, August 1990.

[74]. B. Latane, and J.M. Darley, "Group Inhibition of Bystander Intervention in Emergencies," Journal of Personality and Social Psychology, vol. 10, Issues 3, pp. 215-221, 1968.

[75]. C.D. Wickens, " Engineering Psychology and Human Performance", 2nd Ed, New York: R.R. Donnelley & Sons Company, pp. 258 – 312, 1992.

[76]. S. Heliövaara, J. Kuusinen,, T. Rinne, T. Korhonen, and H. Ehtamo, "Pedestrian behaviour and exit selection in evacuation of a corridor – An experimental study" Safety Science, vol. 50, Issue 2, pp. 221-227, February 2011.

[77]. G. Proulx, "Section 3, Chapter 12 – Behavioural Response to Fire and Smoke" SFPE Handbook of Fire Protection Engineering, Third Edition, Society of Fire Protection Engineers, Bethesda, MD, 2002.

[78]. S. Gwynne, E. Galea, P.J. Lawrence, and L. Filippidis, "Modelling occupant interaction with fire conditions using the building EXODUS Evacuation model." University of Greenwich, London, England, Paper No. 00/IM/54, February 2000.

[79]. T.Korhonen, S.Hostikka, "Fire Dynamics Simulator with Evacuation: FDS+Evac." VTT Technical Research Centre of Finland, 2009.

[80]. J. Burnett, "Fire safety concerns for rail rapid transit systems". Fire Safety Journal, vol. 8, Issue 1, pp. 3-7, November 1984.

[81]. R. Carvel and G. Marlair, "A History of Fire Incidents in Tunnels." The Handbook of Tunnel Fire Safety, ed. Beard, A., and Carvel, R., pub. Thomas Telford, London, pp. 3-37, 2005.

[82]. R. Carvel, and G. Marlair, “A History of Fire Incidents in Tunnels.”, Chapter 2, “Tunnel fire investigation 1: The Channel Tunnel Fire, 18 November 1996”, The Handbook of Tunnel Fire Safety, ed. Beard, A., and Carvel, R., pub. Thomas Telford, London, pp. 42-51, 2005.

[83]. P. Rohén and B. Wahlstrom, “Metro accident in Baku, Azerbaijan October 28, 1995 [The Subway Accident in Baku, Azerbaijan, 28 October 1995] ", the Swedish Rescue [Swedish Rescue Services Agency], Kalstad, 1996.

[84]. D. Nilsson, “METRO - A joint Safety in Infrastructure project between Hungary and Sweden”, Work package 2 – evacuation, 2009. [Online]. Available: http://www.metroproject.se/

[85]. L. Benthorn, and H. Frantzich. “Fire alarm in a public building: How do people evaluate information and choose evacuation exit?”, Department of Fire Safety Engineering, Lund Institute of Technology, Lund University, June 1996.

[86]. K.E. Boyce, D. Purser. and J. Shields. “Experimental Studies to Investigate Merging Behaviour in a Staircase.” University of Ulster, United Kingdom, Human Behaviour in Fire Symposium 2009, pp. 111 – 122, 2009.

[87]. J.S. Tubbs, and B.J. Meacham, “Egress Design Solutions: A Guide to Evacuation and Crowd Management Planning.” John Wiley & Sons, 111 River Street, Hoboken, NJ, Edition 1, 2007.

[88]. Swedish Standard Institution, “Safety in Railway Tunnels”, Official Swedish Journal, Document number c6450. 2007.

[89]. PHASER Scientific Software, “Significance of the R^2 Value”. [Online]. Available: http://www.phaser.com/modules/students/salmon/R2.pdf

[90]. C.D. Wickens and J.G. Hollands, “Engineering psychology and human performance”, Prentice Hall, pp. 243 - 274, 2000.

[91]. Swedish Standard Institution, “Safety in Railway Tunnels”, Official Swedish Journal, Document number c6450. 2007.

[92]. K. Fridolf., E. Ronchi., D. Nilsson., and H. Frantzich. "Movement speeds and exit choice in smoke-filled rail tunnels". [Unpublished].

[93]. H. Ingason, M. Kumm, D. Nilsson, A. Lonnermark, A. Claesson, Y.Z. Li, K. Fridolf, R. Akerstedt, H. Nyman, T. Dittmer, R. Forsen, B. Janzon, G. Meyer, A. Bryntse, T. Carlbery, L. Newlove-Eriksson and A. Palm. "The METRO Project: Final Report", Studies in Sustainable Technology, Research Report, 2012.

[94]. W. Foddy, "Constructing questions for interviews and questionnaires: theory and practice in social research". Cambridge: Cambridge University Press, 1993.

[95]. T.J. Shields, and K.E. Boyce, "A study of evacuation from large retail stores" Fire Safety Journal, vol. 35, Issue 1, pp. 25-49, July 2000.

[96]. P. Xiaoshan, C.S. Ham, K. Dauber and K.H. Law, "Human and social behaviour in computational modelling and analysis of egress". Automation in Construction, vol. 15, Issue 4, pp. 448-461, July 2006.